VOL. 12, NO. 16, AUGUST 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EFFECT OF VORTEX INDUCED VIBRATION ON FATIGUE DAMAGE OF TOP-TENSIONED RISER SUBJECTED TO CURRENT LOAD

Ke Xin Lai[1,2], Do Kyun Kim[1,2,3] and Eileen Wee Chin Wong[1,4]
[1]Ocean and Ship Technology Research Group, Universiti Teknologi Petronas, Seri Iskandar, Malaysia
[2]Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, Seri Iskandar, Malaysia
[3]Graduate School of Engineering Mastership, Pohang University of Science and Technology, Pohang, South Korea
[4]Department of Mechanical Engineering, Universiti Teknologi Petronas, Seri Iskandar, Malaysia

ABSTRACT

Over the last decade, offshore deepwater developments in the oil and gas industry have outrun the onshore and shallow water field developments. Researches, designs, and developments have been focusing on the deepwater environment in recent years. Safe and robust design of structures and systems for offshore deepwater development is relatively complicated due to the impact of high current and wave. Top tension riser (TTR), which is capable to adapt to the superior motions of the vessel, has been a reasonable and advisable option in deepwater field for transporting hydrocarbon from seabed to the platform. Hence, investigation on the effect of current on the fatigue performance of TTR in associated with vortex-induced vibration (VIV) is relatively important, considering VIV as one of the most important factors causing fatigue damage in deepwater TTR. In this study, the effect of uniform and sheared current on the VIV fatigue damage of TTR is studied. It is observed that the VIV fatigue damage increases with increasing current velocity. Besides, parameters such as water depth, riser diameter, and riser wall thickness are varied to investigate the sensitivity of the parameters in the VIV fatigue damage of TTR. The results indicated that VIV fatigue damage increases as the wall thickness increases in the bare riser; whereas the VIV fatigue damage for strake riser shows inconsistencies. Further studies and continuous validation and improvement shall be done to increase the accuracy and precision of this study.

Keywords: TTR, riser diameter, offshore deepwater development.

1. INTRODUCTION

Riser system is essentially conductor pipes connecting the floaters on the surface and the wellheads at the seabed. As petroleum exploration and exploitation move to ever deeper waters, the focus on riser technology is sharpening. According to Jordan, Otten, and Davies [1], the top tensioned riser (TTR) takes advantage of the floater's superior motion characteristics to provide cost-effective flowline risers. The TTR extends substantially vertically from a platform hull to the sea-bottom and they are usually incorporated with the riser length adjustment system at its upper end and the riser tension monitoring systems in the riser porch. With only limited active motions with the TTR, interference between risers and tendons or mooring lines can also be avoided.

As water depth increases, the cost of the riser system and the technological challenges both increase rapidly. One of the main concerns in the design of TTR is the dynamic fatigue loading from the platform motion and ocean currents. Especially in the Gulf of Mexico and offshore Brazil regions where loop currents and hurricanes are often severe, vortex induced vibration (VIV) is a major design issue for all deepwater riser systems [2]. Top tensioned risers may require increased top tension or suppression devices such as helical strakes or fairings to limit the fatigue damage induced by VIV. Besides, it is important to monitor and predict the response of riser at its critical fatigue locations so that the fatigue damage rates can be tracked and controlled.

Fatigue related potential problems are one of the most important factors potentially leading to the structural failure of ships and steel structures. Offshore deepwater risers are often susceptible to fatigue damage due to high cyclic stress imposed by the environmental loadings, such as wind, wave, and current. Current load is the most critical among the environmental loadings because it contributes to the formation of vortex shedding around the riser, thus causing vortex induced vibration (VIV) fatigue damage to the risers. The riser structural response to VIV is complex, especially in the deepwater environment where high multi-mode and frequency responses are expected [3]. Of all the risers, steel catenary riser (SCR) and top-tensioned riser (TTR) are among the most sensitive to environmental loadings. Failure to the riser may lead to spilling of hydrocarbon and production shutdown, and this will subsequently causes pollution, which is detrimental to the safety of the public, economic and the environment. In this study, the focus will be mainly on TTR.

2. VIV OF TOP-TENSIONED RISER

VIV is also commonly understood as the vibration caused by vortex shedding that produces alternating forces on the cylinder. The VIV vortex shedding creates forces in both the cross-wise and stream-wise directions. In-line vibrations are usually not a concern for risers since they appear at lower reduced velocity; whereas the axial vibrations are by-product of cross-flow vibrations and are observed when the axial deformation due to the cross-flow vibrations triggers a resonant axial mode. VIV suppression devices such as helical strakes and fairings should be installed at locations where the response amplitudes are found to be high, such as at the lower part of the riser [4]. This is because the

ARPN Journal of Engineering and Applied Sciences

curvature of this part is large and the stress cycle level is high for a given mode. Thethi *et al.* [3] stated that the critical regions of TTR are areas with high bending moment, which are at the connection to the wellhead at the seabed, on either side of the Spar keel, the conductor below the mud line, as well as at the upper riser in the hull structure. These critical locations exhibit complex responses and they have the lowest predicted fatigue life.

3. VIV ASSESSMENT APPROACHES

Several tools and methods have been introduced to predict the VIV response and the corresponding fatigue damage of the riser system, such as the semi-empirical models, numerical method, experimental studies, as well as 2D and 3D computational fluid dynamics (CFD) simulations. Several state-of-practice softwares such as SHEAR7, VIVA and VIVANA have been widely used by researchers, as well as the industry, to analyse the fatigue performance of riser systems. However, Gabbai and Benoroya [5] stated that the semi-empirical models are not rigorous and generally provide minimal insights into the flow field. Besides, analytical VIV fatigue damage prediction tools are widely recognized by the industry as conservative and there is a considerable gap between the predictions of VIV fatigue analysis tools and the actual field measurements. While it is proven that the 2D CFD solution may not be a good approximation in general [6], 3D CFD simulations demand a great amount of computational time although it provides a better accuracy. Hence, due to inadequate accuracy of the existing methods and their requirement of a great amount of computational time as well as its complicated process, an easy and efficient method to estimate the fatigue damage of riser using field data as the input is veritably required.

Le Cunff *et al*. [7] introduced another alternative that consists of computing the Navier-Stokes equations in slices, neglecting the direct influence between the different slices. This technique is developed based on the time-dependant solution of the structural equation coupled with a model equation for the fluid forcing, and such a method is expected to provide a powerful tool for riser design. Detailed experiments have also been conducted to provide benchmarks test for the various numerical tools at our disposal.

A comprehensive review of fundamental discoveries with respect to VIV has been discussed by Williamson and Govardhan [8]. In a research conducted by Li *et al*. [4], it is suggested that the riser's flexural rigidity, top tension and internal flow velocity have a significant influence on the riser fatigue life. Huang, Chen, and Chen [9] presented a computational fluid dynamics (CFD) approach and the associated case study results of a vertical riser in sheared current. The result shows that the vortex traveling speed varies along the riser, and the vortex travels faster at the riser bottom due to higher current speed compared to at the riser top. It is also observed that there is a slight over-prediction on the response amplitude compared to the experimental data. Howells and Lim [2] criticised the unreliability of the analytical methods in assessing deepwater riser VIV response due to the fact that these analytical tools are developed using small scale test with low Reynolds number which is substantially different from real-life riser and current condition. Trim, Braaten, Lie, and Tognarelli [10] also highlighted the inconsistency of calculated marine riser VIV fatigue damage using computer model with the observed measurement of VIV-related damage.

4. MODELLING OF TTR

The TTR riser model is constructed using semi empirical tool, Orcaflex based on data obtained from Barltrop [11]. A tensioner is added at the top of the riser and the bottom of the riser is anchored at the seabed. Static configuration analysis of the riser is then conducted without environmental loading to obtain the equilibrium configuration of the riser upon the exertion of static loading such as weight and buoyancy of the riser. VIV suppression devices, strakes, are then added onto the riser system with 80% coverage along the TTR, and followed by the environmental loadings

The focus of this study mainly emphasizes on the short-term VIV fatigue damage experienced by the riser structure. The VIV fatigue analysis is conducted on a TTR model constructed based on an imaginary environment created with the assumption such that the riser is installed in the Gulf of Mexico (GOM). The design of the riser model is constructed in accordance with the design codes and standards from API and DNV. Semi empirical tool, OrcaFlex, is used to construct the model and to run analytical simulations. SHEAR7 is used in conjunction with OrcaFlex to compute the total fatigue damage of the riser caused by VIV.

Study is performed to investigate the effect of variation of only the current profile parameter. Of particular relevance is the current magnitude and shape to the VIV response of the riser. Variation of wave and wind data will not be taken into consideration in this study and thus, these data will be fixed for all scenarios.

Table-1. TTR structural data [11].

Parameters	Data value
Outer Diameter (m)	0.5
Wall Thickness (mm)	15
External Area, A_{ext} (m^2)	0.196
Internal Area, A_{int} (m^2)	0.173
Riser Weight in Air, W_{air} (kN)	933
Riser Submerged Weight, $W_{submerged}$ (kN)	-54
Riser Material	Steel
Material Density (tonne/m^3)	7.85
Water Density (tonne/m^3)	1.025
Internal Fluid Density (tonne/m^3)	0.9
Internal Fluid Pressure (MPa)	6.895

ARPN Journal of Engineering and Applied Sciences

By comparing the wall tension and effective tension of the riser shown in the book and the results obtained from Orcaflex on the constructed TTR model, it is observed that the values are comparable. Thus, this has validated that the constructed TTR model to be accurate.

5. VIV FATIGUE ANALYSIS

A. Investigation of the effect of current load on the VIV fatigue damage of TTR

VIV suppression devices, strakes, are then added and VIV fatigue analysis is conducted for uniform current profile as the base case for this study. The uniform current velocities used for the analysis were 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 m/s. VIV fatigue analysis is then conducted for 1, 10, and 100 year loop current data obtained from a thesis paper by Park [12].

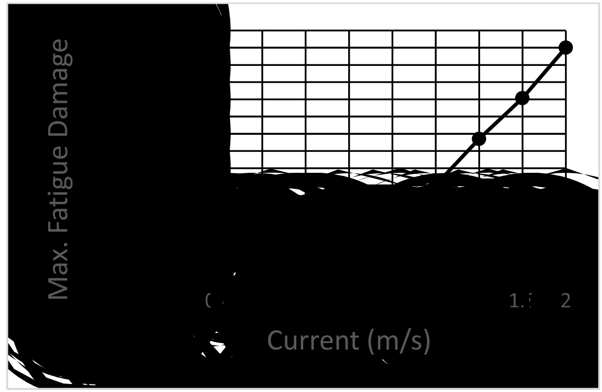


Figure-1. VIV fatigue damage due to uniform current load.

It is observed that the maximum fatigue damage of riser increases with the increasing current. The maximum fatigue damage has exceeded the allowable value of 1 when the current velocity is more than about 1.2 m/s.

Table-2. Loop current data [12].

1-year loop current		**10-year loop current**		**100-year loop current**	
Depth (m)	**Speed** (m/s)	**Depth** (m)	**Speed** (m/s)	**Depth** (m)	**Speed** (m/s)
0	1.15	0	1.54	0	2.07
50	1.14	50	1.53	50	2.05
60	1.09	60	1.46	60	1.97
70	1.04	70	1.39	70	1.86
80	0.98	80	1.31	80	1.76
90	0.92	90	1.23	90	1.66
100	0.85	100	1.14	100	1.53
150	0.62	150	0.83	150	1.12
200	0.49	200	0.66	200	0.89
250	0.40	250	0.54	250	0.72
300	0.35	300	0.47	300	0.62
400	0.28	400	0.38	400	0.50
500	0.23	500	0.31	500	0.41

VOL. 12, NO. 16, AUGUST 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

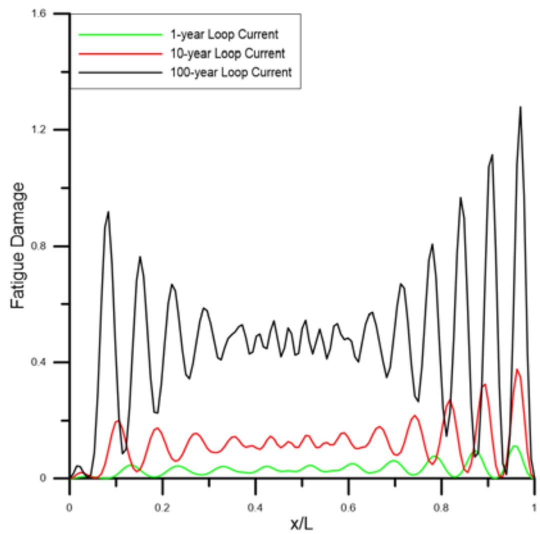


Figure-2. VIV fatigue damage due to loop current.

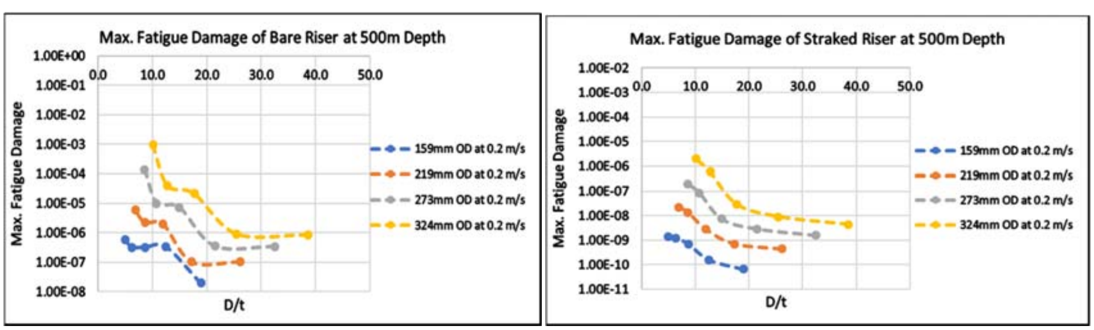
It is observed that the maximum fatigue damage due to the 100-year loop current has exceeded the allowable value of 1 at the bottom of the riser.

B. Analysis of VIV fatigue damage of TTR due to uniform current load with varying riser diameter and riser wall thickness

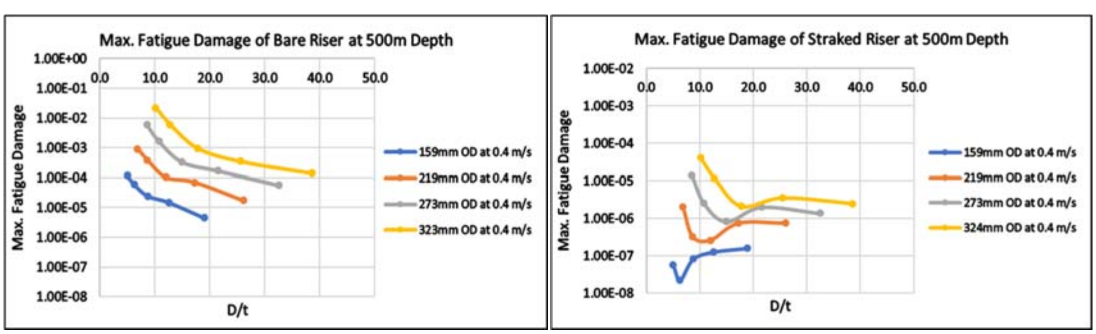
The VIV fatigue damage analysis is repeated by varying the riser outer diameter (OD) with 159mm, 219.1mm, 273mm, and 323.9mm, and for each value of riser outer diameter, the analysis is repeated by varying the riser wall thickness with 8.4mm, 12.7mm, 18.3mm, 25.4mm and 32mm as shown in Figure-3. Uniform current load of 0.2m/s, 0.4m/s, and 0.6m/s are also repeated for each case. The results are shown in terms of the riser diameter to thickness ratio against fatigue damage. All the analysis is conducted at different water depths, which are 500m, 1000m, 1500m, and 2000m. The analysis is also conducted on riser with 80% strake coverage.

The results obtained from the analysis indicate that the VIV fatigue damage of riser increases as the riser outer diameter increases. Moreover, as the current velocity increases, the riser fatigue damage increases as well. The results obtained shows similar trends in all water depths.

The VIV fatigue damage of strake riser shows inconsistency in the some of the results obtained. Unlike bare riser, which the VIV fatigue damage decreases with the increasing riser diameter to wall thickness ratio, some cases for strake riser show increment in VIV fatigue damage as the riser diameter to wall thickness ratio increases. This is most probably because of the change in riser structural properties as strakes are installed on the riser, which subsequently changes the natural frequency and exciting modes of the riser, thus affecting the fatigue damage of the riser. Further studies on riser natural frequency and exciting modes needs to be done to obtain detailed explanation.



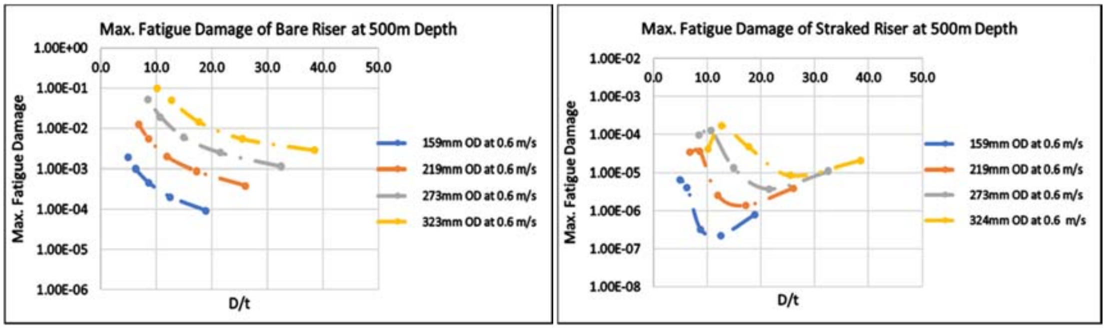
(a) VIV fatigue damage at 500m depth with 0.2m/s current.



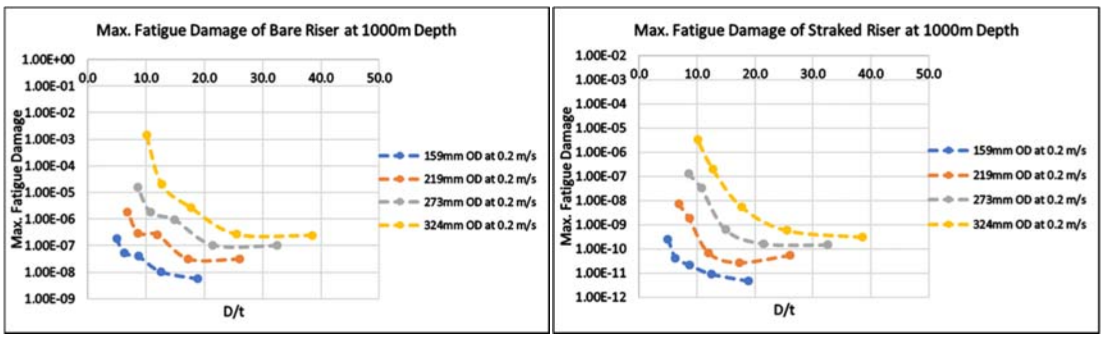
(b) VIV fatigue damage at 500m depth with 0.4m/s current.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

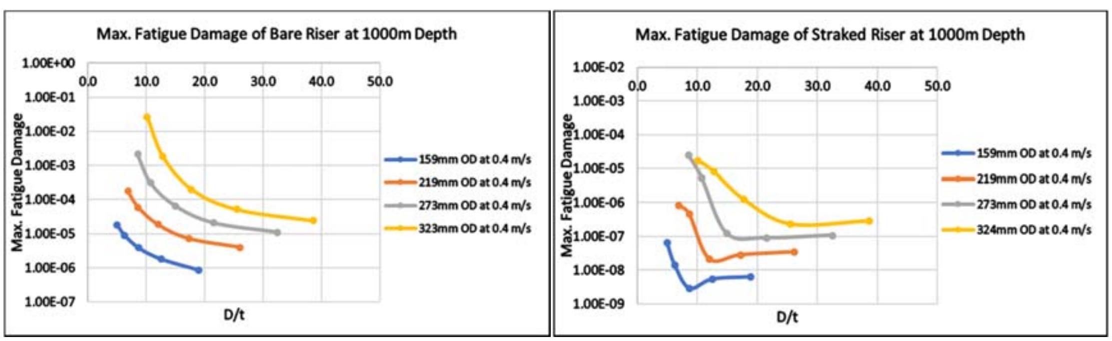
www.arpnjournals.com



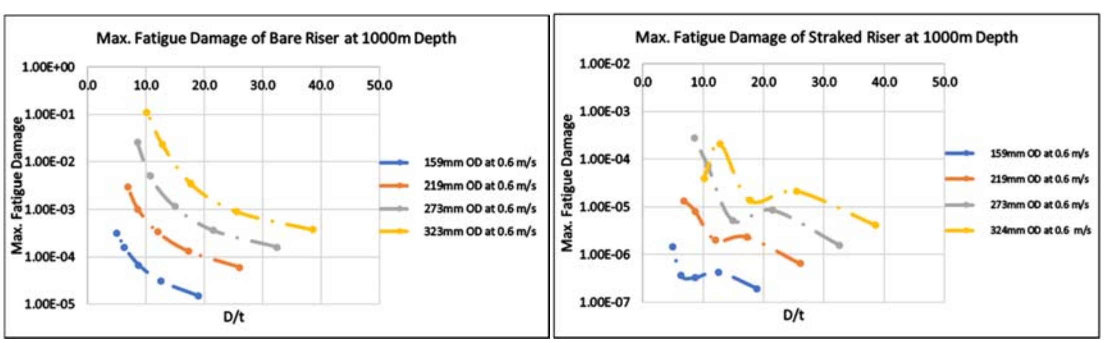
(c) VIV fatigue damage at 500m depth with 0.6m/s current.



(d) VIV fatigue damage at 1000m depth with 0.2m/s current.

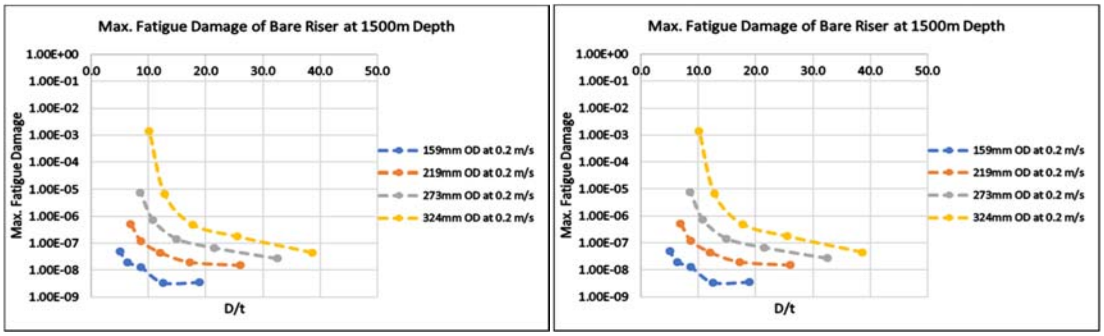


(e) VIV fatigue damage at 1000m depth with 0.4m/s current.

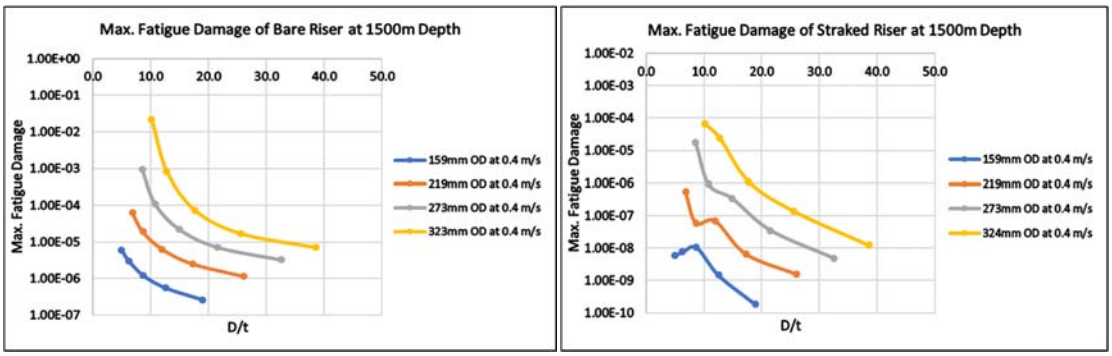


(f) VIV fatigue damage at 1000m depth with 0.6m/s current.

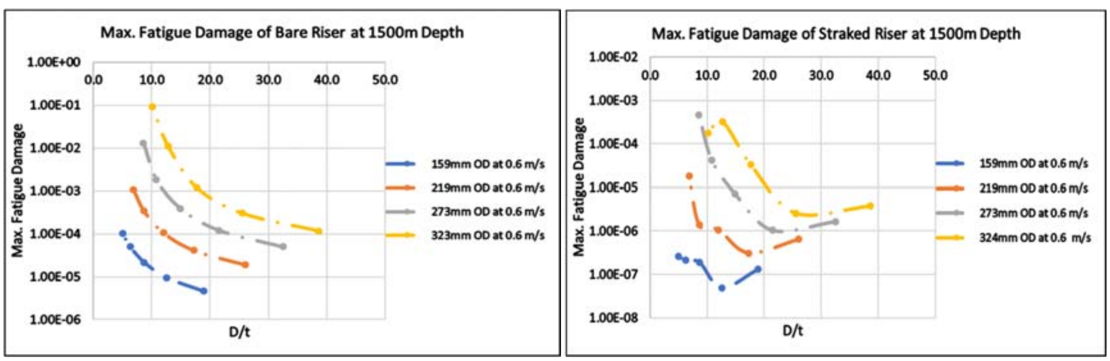
ARPN Journal of Engineering and Applied Sciences



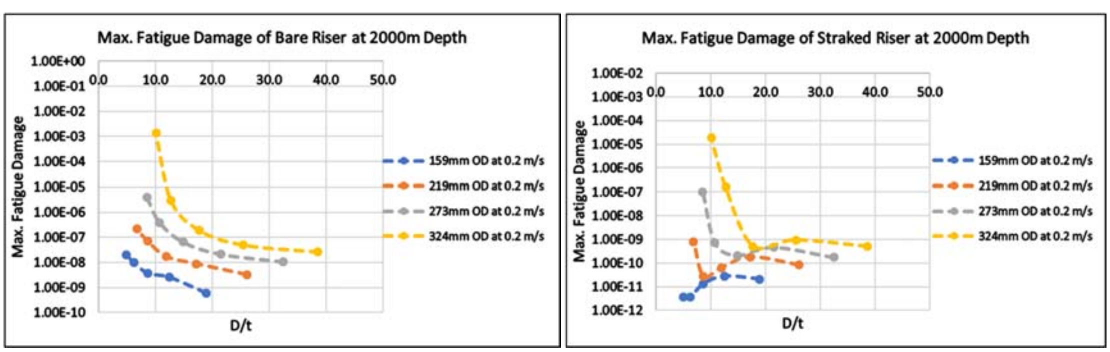
(g) VIV fatigue damage at 1500m depth with 0.2m/s current.



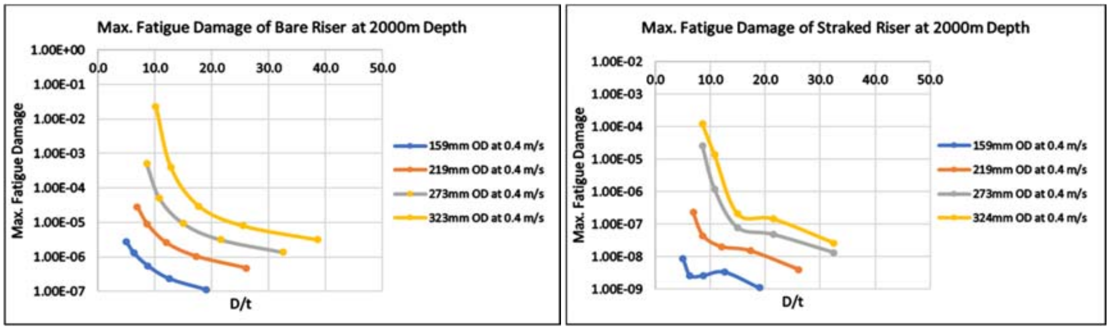
(h) VIV fatigue damage at 1500m depth with 0.4m/s current.



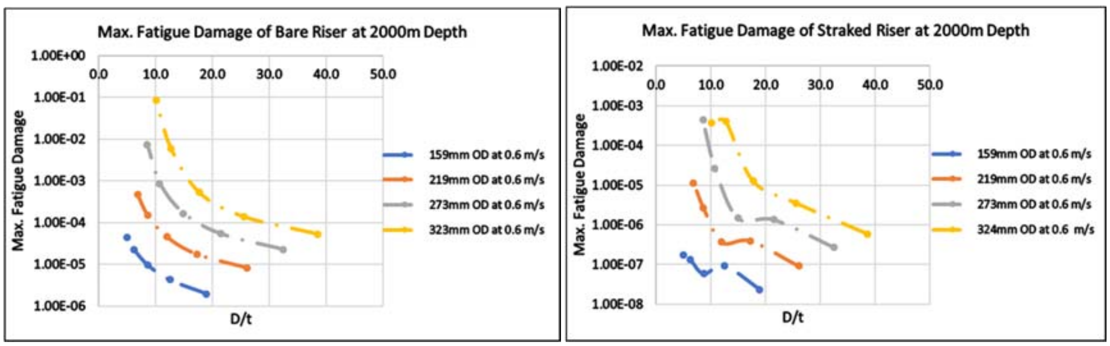
(i) VIV fatigue damage at 1500m depth with 0.6m/s current.



(j) VIV fatigue damage at 2000m depth with 0.2m/s current.



(k) VIV fatigue damage at 2000m depth with 0.4m/s current.



(l) VIV fatigue damage at 2000m depth with 0.6m/s current.

Figure-3. Calculated fatigue damages.

6. CONCLUSION AND RECOMMENDATION

In this study, top-tensioned riser (TTR) model is constructed and the VIV fatigue analysis is conducted for different current velocities. Parametric studies are conducted to study the effect of current velocity on the VIV fatigue damage of TTR. From the VIV fatigue analysis, it is concluded that the maximum fatigue damage increases with current velocity. Hence, the relationship between the current velocity and maximum fatigue damage can be expressed in the form of empirical equation, which maximum fatigue damage is proportional to current velocity. The effect of varying riser diameter and riser wall thickness with uniform current on the VIV fatigue damage of TTR is determined.

It is recommended that the variation in the direction of current to be investigated in future work in order to get more precise estimation of VIV fatigue damage on TTR. Effect of other VIV parameters and riser structural properties to the VIV fatigue damage of TTR shall be performed. Further studies on riser natural frequency and exciting modes needs to be done to obtain detailed understanding on the VIV fatigue damage of TTR. Continuous validation and improvement shall be done to increase the accuracy and precision of this study.

ACKNOWLEDGEMENTS

This study was undertaken at Ocean and Ship Technology (OST) under Deepwater Technology Mission Oriented Research at Universiti Teknologi Petronas. This research was supported by the Technology Innovation Program (Grant No.: 10053121 and 10051279) funded by the Ministry of Trade, Industry & Energy (MI, Korea) and YUTP Grant (0153AA-E60, Malaysia). The authors would also like to thank for the great support of POSTECH, POSCO, and Daewoo E & C, Republic of Korea.

REFERENCES

[1] Jordan T. R., Otten J. D. and Davies K. B. 2006. Top tensioned riser. Google Patents.

[2] Howells H. and Lim F. 1999. Deepwater riser VIV monitoring. Advances in Riser Technologies, IBC, Aberdeen.

[3] Thethi R., Howells H., Natarajan S. and Bridge C. 2005. A fatigue monitoring strategy and implementation on a deepwater top tensioned riser. In: Offshore Technology Conference.

[4] Li X., Guo H. and Meng F. 2010. Fatigue life assessment of top tensioned risers under vortex-induced vibrations. Journal of Ocean University of China. 9(1): 43-47.

[5] Gabbai R. and Benaroya H. 2005. An overview of modeling and experiments of vortex-induced vibration of circular cylinders. Journal of Sound and Vibration. 282(3): 575-616.

ARPN Journal of Engineering and Applied Sciences

[6] Holmes S., Oakley O. H. and Constantinides Y. 2006. Simulation of riser VIV using fully three dimensional CFD simulations. In: The 25th International Conference on Offshore Mechanics and Arctic Engineering.

[7] Le Cunff C., Biolley F., Fontaine E., Etienne S. and Facchinetti M. 2002. Vortex-induced vibrations of risers: theoretical, numerical and experimental investigation. Oil & Gas Science and Technology. 57(1): 59-69.

[8] Williamson C. and Govardhan R. 2008. A brief review of recent results in vortex-induced vibrations. Journal of Wind Engineering and Industrial Aerodynamics. 96(6): 713-735.

[9] Huang K., Chen H. C. and Chen C. R. 2012. Vertical riser VIV simulation in sheared current. International Journal of Offshore and Polar Engineering. 22(02).

[10] Trim A., Braaten H., Lie H. and Tognarelli M. 2005. Experimental investigation of vortex-induced vibration of long marine risers. Journal of Fluids and Structures. 21(3): 335-361.

[11] Barltrop N. D. P. 1998. Floating structures - A guide for design and analysis, Volumes 2.

[12] Park K. S. 2014. Fatigue performance of deepwater steel catenary riser. Pohang University of Science and Technology.