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Fatigue performance of deepwater SCR under short-term VIV considering various S-N curves

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Abstract. In this study, a method for fatigue performance estimation of deepwater steel catenary riser (SCR) under short-term vortex-induced vibration was investigated for selected S-N curves. General tendency between S-N curve capacity and fatigue performance was analysed. SCRs are generally used to transport produced oil and gas or to export separated oil and gas, and are exposed to various environmental loads in terms of current, wave, wind and others. Current is closely related with VIV and it affects fatigue life of riser structures significantly. In this regards, the process of appropriate S-N curve selection was performed in the initial design stage based on the scale of fabrication-related initial imperfections such as welding, hot spot, crack, stress concentration factor, and others. To draw the general tendency, the effects of stress concentration factor (SCF), S-N curve type, current profile, and three different sizes of SCRs were considered, and the relationship between S-N curve capacity and short-term VIV fatigue performance of SCR was derived. In case of S-N curve selection, DNV (2012) guideline was adopted and four different current profiles of the Gulf of Mexico (normal condition and Hurricane condition) and Brazil (Amazon basin and Campos basin) were considered. The obtained results will be useful to select the S-N curve for deepwater SCRs and also to understand the relationship between S-N curve capacity and short-term VIV fatigue performance of deepwater SCRs.

Keywords: S-N curve; steel catenary riser (SCR); vortex-induced vibration (VIV); offshore riser engineering, riser fatigue

1. Introduction

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The demand of steady energy resource shows a momentum to move from onshore to offshore from mid of 20th century. From the 21st century, it has been reported that vertical and horizontal drilling technologies of about 10 km under the seabed with water depth of 3 km have been developed for offshore oil and gas sector. The risers, flowlines and pipelines are the optimum transportation structures and their demands are continuously increasing

For the production of offshore oil and gas, the risers can be classified into production riser, which functions as a connector between platforms and subsea manifold structure or wellhead, and also export riser, which is used for transportation of separated oil and gas from the offshore platforms to pipeline. Both risers are exposed to various environmental loads as well. Among the environmental loads, current speed distributions from waterline to seabed are closely related with vortex-induced vibration (VIV) and it would affect the fatigue life of riser structures. With regard to VIV and riser behaviours, various studies have being carried out.

Sarpkaya (2004) reviewed the overall picture of VIV behaviour of circular cylindrical structures by theoretical, experimental, and numerical methods. Lim and Howells (2000) mentioned the experimental research should be performed to investigate real phenomenon of VIV because at that time, the real test results were very rare and most of the test results were obtained by small-scale test with low Reynolds number.

In order to reduce the effect of VIV, research for suppression method is also widely performed. Allen *et al*. (2004) performed an experimental study to investigate the performance of helical strake. Valdiver *et al*. (2006) also conducted an experimental study in order to identify the strake effect by bare riser and straked riser. Rao *et al*. (2012) studied the performance of fairing on VIV behaviour for flexible cylinders.

Recently, Lejlic (2013) investigated VIV fatigue damage effect on riser's touchdown zone (TDZ). Randolph and Quiggin (2009), Yu *et al*. (2013, 2015), Shiri (2014), Kim (2014) extensively researched seabed effect using nonlinear soil model. Particularly, Elosta *et al*. (2013a) studied the interaction between riser and soil using a nonlinear hysteretic model under random loads. In addition, wave induced fatigue damage of pipelines was investigated by Elosta *et al*. (2013b).

It is important to understand thoroughly the applied action and action effect for the structural

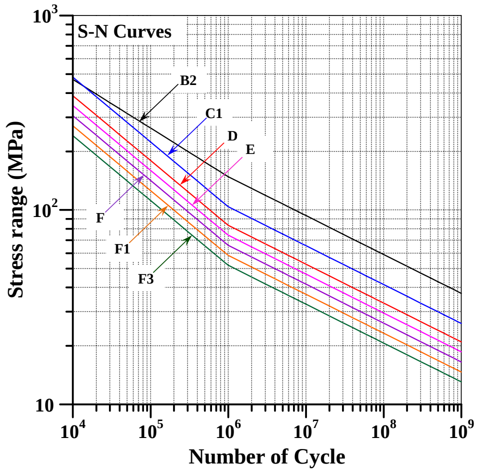


Fig. 1 S-N curves for the design of deepwater riser (DNV 2012)

design of riser. In addition, potential uncertainties should be considered for robust design of various infrastructures. The riser structural design is progressed based on real measuring environment data obtained in the exploration stage and especially the selection of the S-N curve, which dominantly affects fatigue characteristic, therefore should be carefully conducted based on type and completeness of welding.

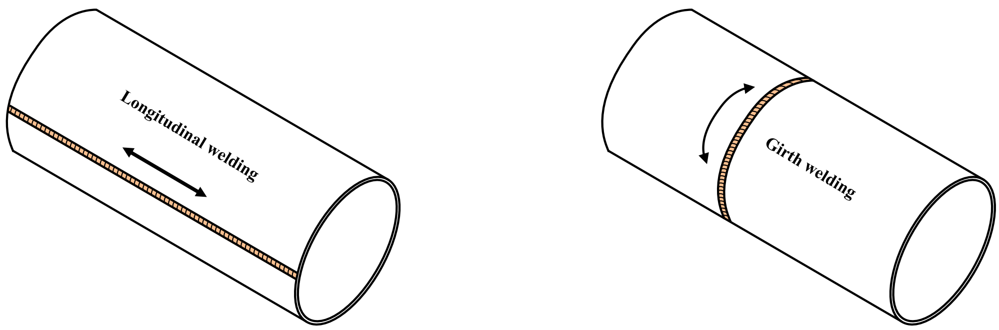
For example, in a case of real offshore riser design field, they recommend E-type S-N curve for the SCR design, but sometimes C-type is also used by the judgment of undertaking engineer. It is, however, the effects of each S-N curve on fatigue performance of deepwater SCR are rarely analyzed and more research are required. In this regards, the effect of S-N curve by type, in water or in air case, on VIV fatigue life was analysed and finally the empirical formulas were proposed in this paper. Four different sea states and their current profiles, i.e., GOM normal, GOM Hurricane, Brazil Amazon, and Brazil Campos, were applied to the three different sizes of SCRs; 8 inch, 10 inch and 20 inch. The obtained results could be useful data to understand the relationship between S-N curve and VIV fatigue performance of deepwater SCRs.

2. S-N curves for deepwater riser design

In general, various components, e.g., base metal or weld, welding quality, weld details and tolerance, weld type, constructional detail, fabrication process, hotspot, stress concentration factor, thickness, and environmental effect, should be considered for selecting the S-N curve at the structural design stage of SCRs (DNV 2010a, 2012).

For the selection of S-N curve, various rules or guidelines, e.g., Det Norske Veritas (DNV), American Petrorium Institute (API), British standard (BS), Human, Safety and Environment (HSE) and others, are applied depending on welding type and structural shape. Among them, only DNV guideline (DNV 2012) was applied to investigate the fatigue performance of SCRs by S-N curve types in the present study. The specified S-N curve types and characteristics are presented in Fig. 1.

Six types of S-N curve, i.e., C1, D, E, F, F1 and F3, regarding hollow section are targeted for the VIV induced fatigue performance of SCRs. The detail of each hollow section's shape is presented in Fig. 2. The S-N curves for welded structure are selected (DNV 2012). It is specified by two conditions of S-N curves, such as in air and in seawater with cathodic protection. In the



(a) Longitudinal welding (B2) (b) Girth welding (C1, D, E, F, F1, F3)

Fig. 2 Details of hollow section of each S-N curve (DNV 2012)

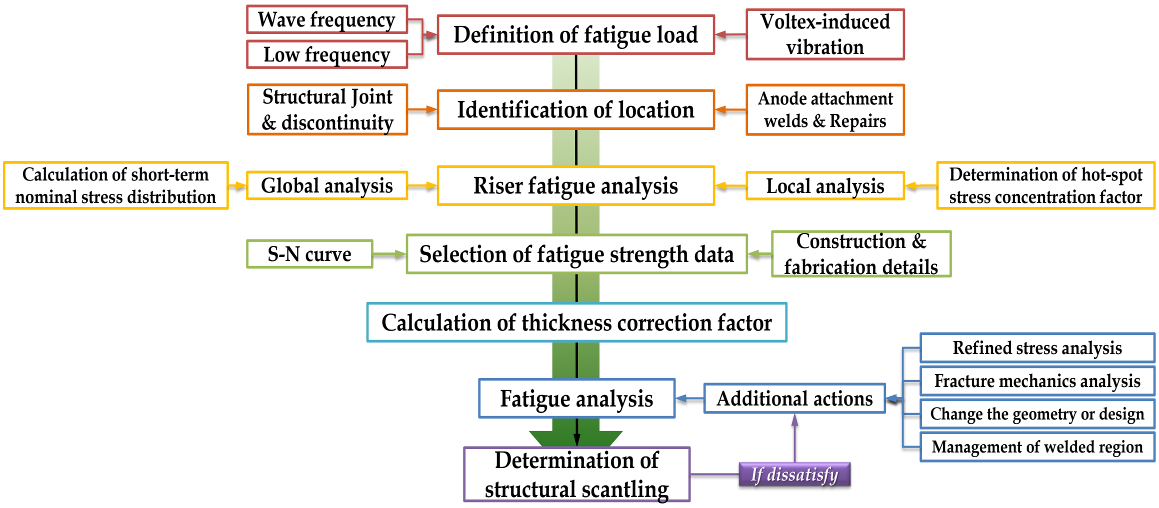


Fig. 3 General procedures for fatigue assessment of deepwater risers (DNV 2010b)

present study, only seawater cases are considered for the analysis of VIV fatigue performance of SCRs.

As the S-N curve is selected, Stress Concentration Factor (SCF) should be calculated. To the exclusion of D-type S-N curve, the SCF of 1.0 is applied for the other five types of S-N curves (C1, E, F, F1, and F3). In this study, only girth welding types are considered. The method for calculating the SCF for D-type S-N curve can be summarized as follows (DNV 2012).

$$SCF = 1.0 + \frac{3\delta_m}{t_w} e^{-\sqrt{t_w/OD}} \tag{1}$$

where, SCF = stress concentration factor; δ_m= maximum misalignment ($\delta_m = \sqrt{\delta_T^2 + \delta_{OV}^2}$); δ_T= maximum misalignment of thickness (($t_{w\text{-max}}-t_{w\text{-min}}$)/2); δ_{OV}= maximum misalignment of ovality; $OD_{\max}-OD_{\min}$ for no pipe centralizing; ($OD_{\max}-OD_{\min}$)/2 for centralized pipe during construction; ($OD_{\max}-OD_{\min}$)/4 for centralized pipe during construction and rotated until a good fitting); t_w=wall thickness; OD=outer diameter.

3. Method for fatigue assessment by vortex-induced vibration

The general fatigue assessment procedure is presented in Fig. 3. As mentioned before, vortex-induced vibration (VIV) was targeted for fatigue load in the present study. During the last two decades, several numerical simulation codes, e.g., SHEAR7, VIVANA, VIVA and others, have been developed and commercialized for the analysis of VIV fatigue using frequency domain method. Recently, time-domain based analysis method such as OrcaFlex is also becoming popular due to improvement of computer performance. In addition, since mid-1990, computational fluid dynamics (CFD) method is used to calculated drag (C_D) and lift (C_L) coefficients. One of the fastest growing methods for dynamic analysis of various structures in ships and offshore industry is fluid-structure interaction (FSI) method, which is related to finite element method (FEM) and

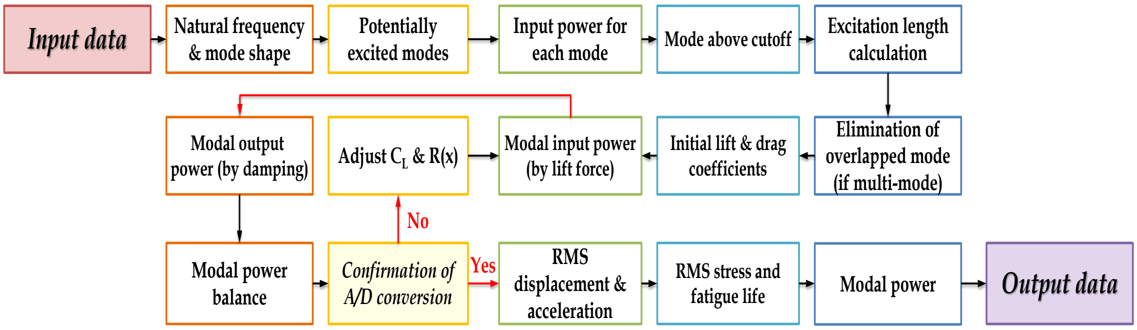


Fig. 4 Procedures for SHEAR7 superposition solution (Vandiver 1999)

CFD.

In the present study, SHEAR7, which is mainly used to the oil and gas industry, was adopted to analyse the VIV fatigue performance of SCRs. The procedures of VIV analysis by SHEAR7 numerical code can be summarized as Fig. 4. The details may be referred to program manual (Vandiver 1999).

4. VIV analysis and corresponding results

4.1 Applied examples and other considerations

The structural, environmental characteristics and seabed profile should be defined in order to analyse the VIV fatigue performance of SCRs. It is not easy to consider all kinds of variables with respect to the abovementioned three conditions. In this regard, only three types of SCRs with four types of representative current profiles were selected for the applied examples shown in Table 1 and Fig. 5.

Two typical types of deepwater SCRs such as export SCR and production SCRs were considered. It is well known that production SCR transports unrefined oil and gas from reservoir to the floating structure and export SCR deals with refined oil from floating structure to the onshore facility. In this regard, export SCR has large outer diameter of pipe compared to production SCR as shown in Table 1. In addition, VIV suppression devices such as strake, fairing, etc. are adopted as function as reducing motion of SCR. The strake is one of the efficient tool which is mostly used in offshore field, in general. Table 1 represents characteristics of adopted three types of strakes in the present study. In case of strake coverage or strake length, 80% of the arc length from the top end to touchdown point is applied based on rule of thumb.

The calculated SCF for three types of SCRs are presented in Table 2. The calculated SCF values were in the range of 1.33 to 1.38. For the research purpose, the range from 1.0 to 2.0 was considered for the analysis of fatigue performance using D-type S-N curve.

It is well known that current load causes the most significant effect on VIV fatigue performance of SCRs (Park 2014, Park *et al*. 2015a, b) compared to other loads such as wind, wave and others. With this respect, it was assumed that the selected three types of SCRs were exposed to four different sea states according to Fig. 5. The water depth and environmental load conditions, e.g., wave height, wind speed and current profiles, were different respectively, but the

Table 1 Characteristics of target structures (MCS 2005)

		Parameter	Case 1	Case 2	Case 3
		Purpose	Gas Export SCR	Gas Production SCR	
pipe properties		Outer diameter (mm)	508 (20-inch)	273 (10-inch)	219 (8-inch)
		Inner diameter (mm)	446.5	213.1	170.8
		Wall thickness (mm)	30.7	30.0	24.1
		Outer diameter / wall thickness	16.55	9.10	9.09
		Corrosion allowance (mm)	1.3	1.6	1.6
		Density (kg/m^3)	7,850		
		Yield strength (MPa)	448.2		
		Poisson ratio	0.3		
		Young's modulus (GPa)	204.8		
Coating properties	Touchdown zone	Density (kg/m^3)	1393.6	1441.7	
		Thickness (mm)	2.54	3.175	
	Bare pipe zone	Density (kg/m^3)	1393.6	1441.7	
		Thickness (mm)	0.4064	0.5588	
Strake properties		Barrel diameter (mm)	25.006	29.997	29.591
		Equivalent diameter (mm)	4.673	5.340	6.928
		Density (kg/m^3)	1151	1150	1151

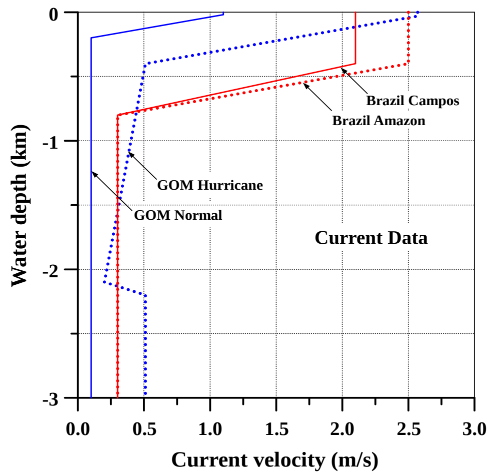


Fig. 5 Selected four representative current data (Bai and Bai 2010)

Table 2 Calculated stress concentration factors for SCRs

SCR types	$t_{w\text{-max}}$ (mm)	$t_{w\text{-min}}$ (mm)	$OD_{\max}$ (mm)	$OD_{\min}$ (mm)	Stress concentration factor: D-type S-N curve	Stress concentration factor: Others
20 in	36.88	28.28	511.81	506.73	1.381	1.0
10 in	35.97	27.57	275.10	271.00	1.336	1.0
8 in	28.96	22.20	220.72	217.43	1.335	1.0

Note: SCR = steel catenary riser, $t_{w\text{-max}}$ = maximum wall thickness, $t_{w\text{-min}}$ = minimum wall thickness, $OD_{\max}$=maximum outer diameter, and $OD_{\min}$ = minimum outer diameter.

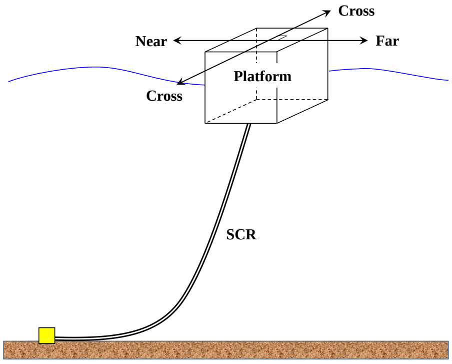


Fig. 6 Schematic of vessel motion for VIV analysis

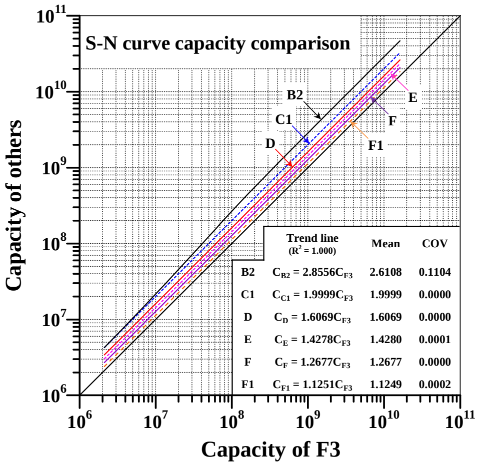


Fig. 7 Comparison of S-N curve capacity between F3 and others

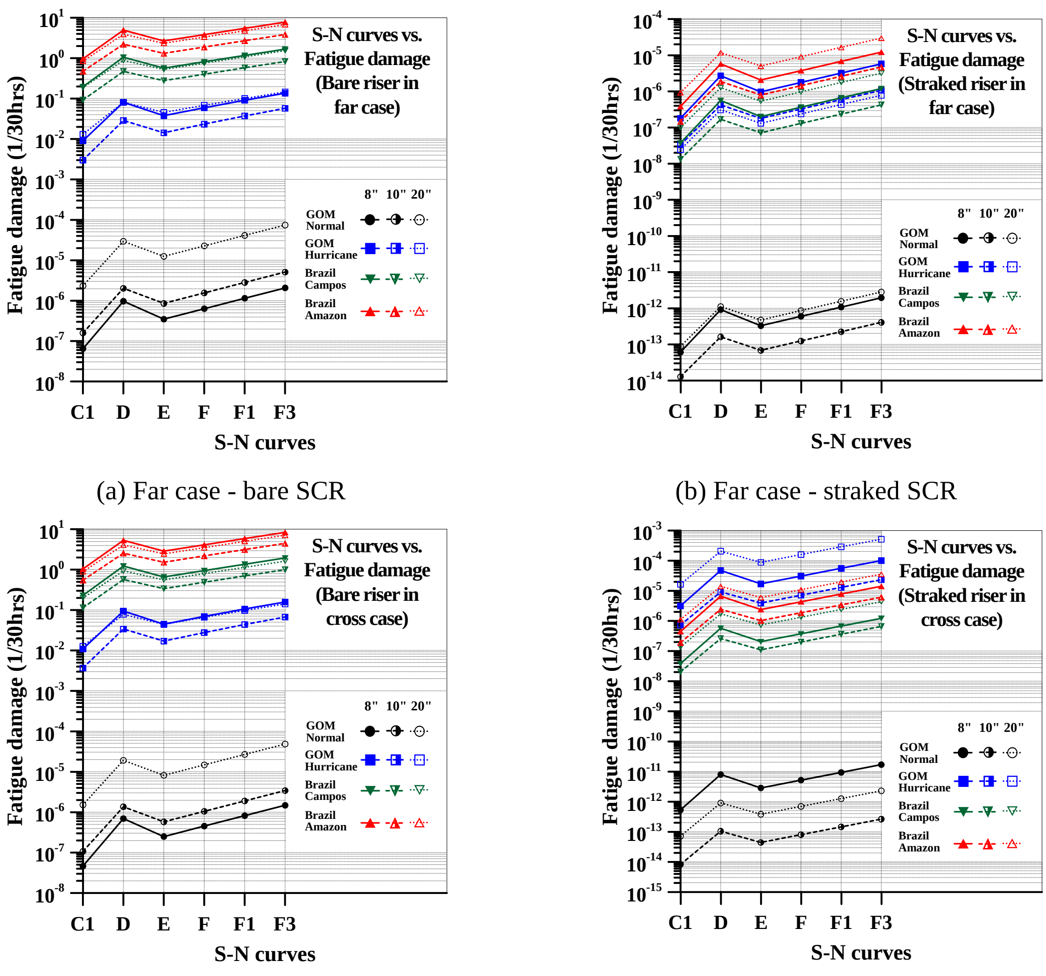
same water depth of 2,500 m was applied to all SCRs. In case of wave and wind loads, a small amount of values, i.e., 0.1 m for wave height and 0.1 m/s for wind speed, were assumed. In addition, three types of SCR motion, i.e., near, far, and cross, has been applied to the VIV analysis as shown in Fig. 6.

4.2 VIV fatigue analysis results of SCRs

In first step, a comparison made for S-N curve capacities between F3 and others was shown in Fig. 7. It was approximately assumed that the interval of number of cycle of 10 was selected to investigate the difference between F3 and other types of S-N curves. The trend line, mean and COV values were produced as well. It was generally found that the difference showed linear relations between F3 and others except for B2 curve. In case of B2 curve which was not applied for VIV fatigue analysis, the range of number of cycle between 10^4 to 10^6 showed different trend compared with others in Fig. 1 and it caused nonlinear behaviour in Fig. 7. In this present study, only girth welding types shown in Fig. 2(b) have been considered. The obtained differences will be compared with fatigue performance of deepwater risers subjected to vortex-induced vibrations.

Fatigue damages (1/30hrs) for bare SCRs were calculated and plotted based on each S-N curve for the comparison purpose shown in Fig. 8(a), (c), (e), and (g) which covers 3 types of SCR motion and maximum fatigue damage. Once again, only short-term VIV with 30 hrs has been considered in the present study based on Park (2014). As would be expected, the fatigue performance was getting better from the F3 to C1-type S-N curve except for D-type. This means that fatigue damage, which was in inverse proportion to fatigue life, had increased. In case of D-type, stress concentration factor (SCF) should be calculated based on Eq. (1). The SCF value of 1.0 was applied to the other types of S-N curves.

In the same way, fatigue damages (1/30hrs) for straked SCRs were also calculated by each S-N curve as shown in Fig. 8(b), (d), (f), and (h). As expected, similar trend but improvements of fatigue performance about 10^4 to 10^7 have been observed. The lowest fatigue performance was observed when the GOM Hurricane current was applied. In case of GOM normal condition, it showed relatively high fatigue performance than others. From this result, fatigue performance of



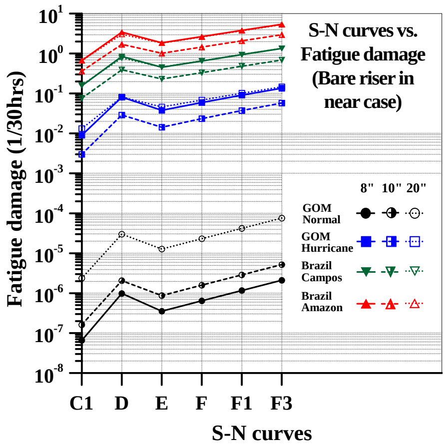
(a) Far case - bare SCR

(b) Far case - straked SCR

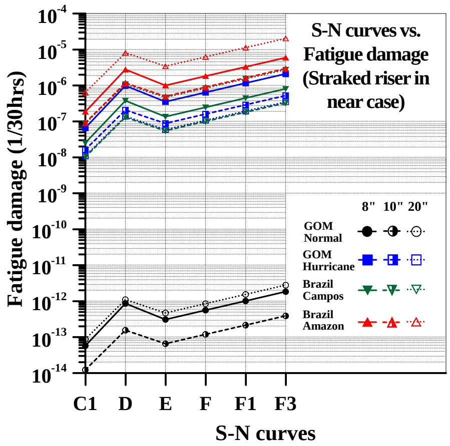
(c) Cross case - bare SCR

(d) Cross case - straked SCR

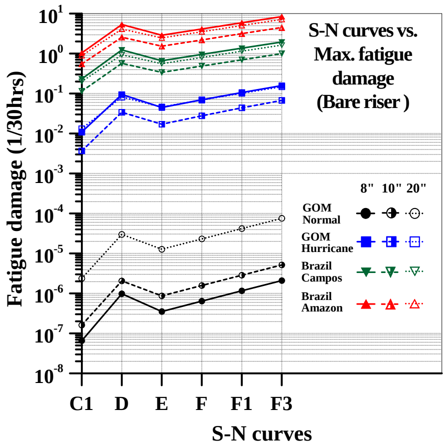
Fig. 8 Comparison of fatigue performance for bare SCR with regard to S-N curve type



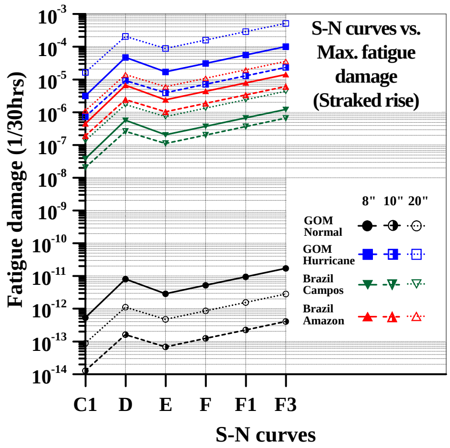
(e) Near case - bare SCR



(f) Near case - straked SCR



(g) Maximum case - bare SCR



(h) Maximum case - straked SCR

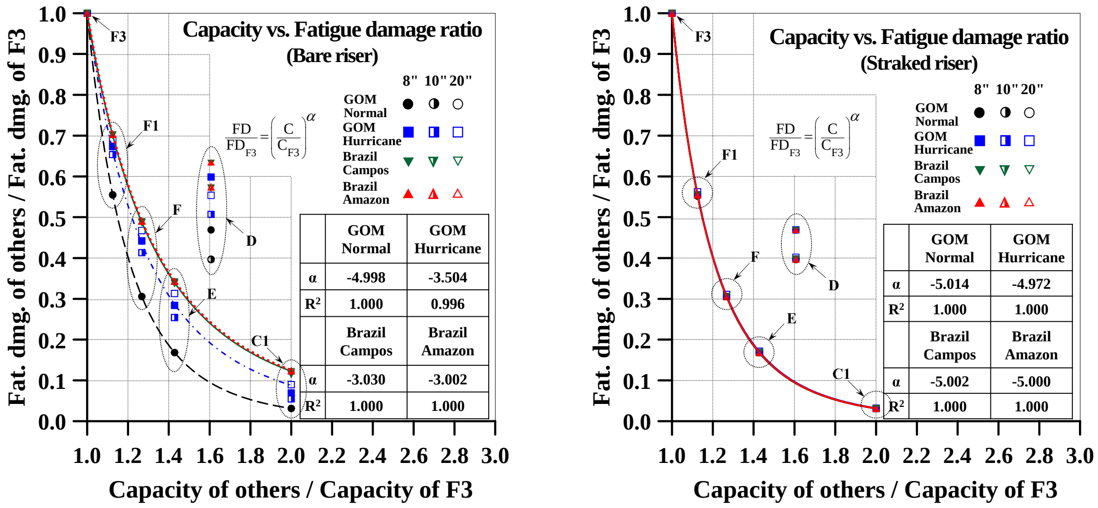
Fig. 8 Continued

deepwater riser is significantly affected by current profile. In addition, the effect of current should be investigated closely.

The fatigue performance of all bare and straked SCRs under Brazil sea states, e.g., Amazon and Campos, showed similar trends. The lowest fatigue performance was observed when the GOM Hurricane current was applied. In case of GOM normal condition, it showed relatively high fatigue performance than others.

Fig. 9(a) and (b) represent the summarized VIV fatigue performances according to the four different current profiles as illustrated in Fig. 5. In order to draw a general trend, F3-type S-N curve was selected as a reference point based on the fatigue capacity. Based on the non-dimensional analysis, empirical formulas were obtained as follows.

$$\frac{FD}{FD_{F3}} = \left(\frac{C}{C_{F3}}\right)^{\alpha} \tag{2}$$



(a) Bare SCR (b) Straked SCR

Fig. 9 Relationship between S-N curve capacity and fatigue damage for bare SCR

where, FD=fatigue damage, FD_{F3}=fatigue damage by F3-type S-N curve, C=fatigue resistance capacity, C_{F3}=fatigue resistance capacity of F3 type S-N curve, and α=current correction factor.

For bare SCR

$$\alpha = \begin{cases} -4.998 & \text{for GOM Normal} \\ -3.504 & \text{for GOM Hurricane} \\ -3.030 & \text{for Brazil Amazon} \\ -3.302 & \text{for Brazil Campos} \end{cases} \quad (3.1)$$

For straked SCR

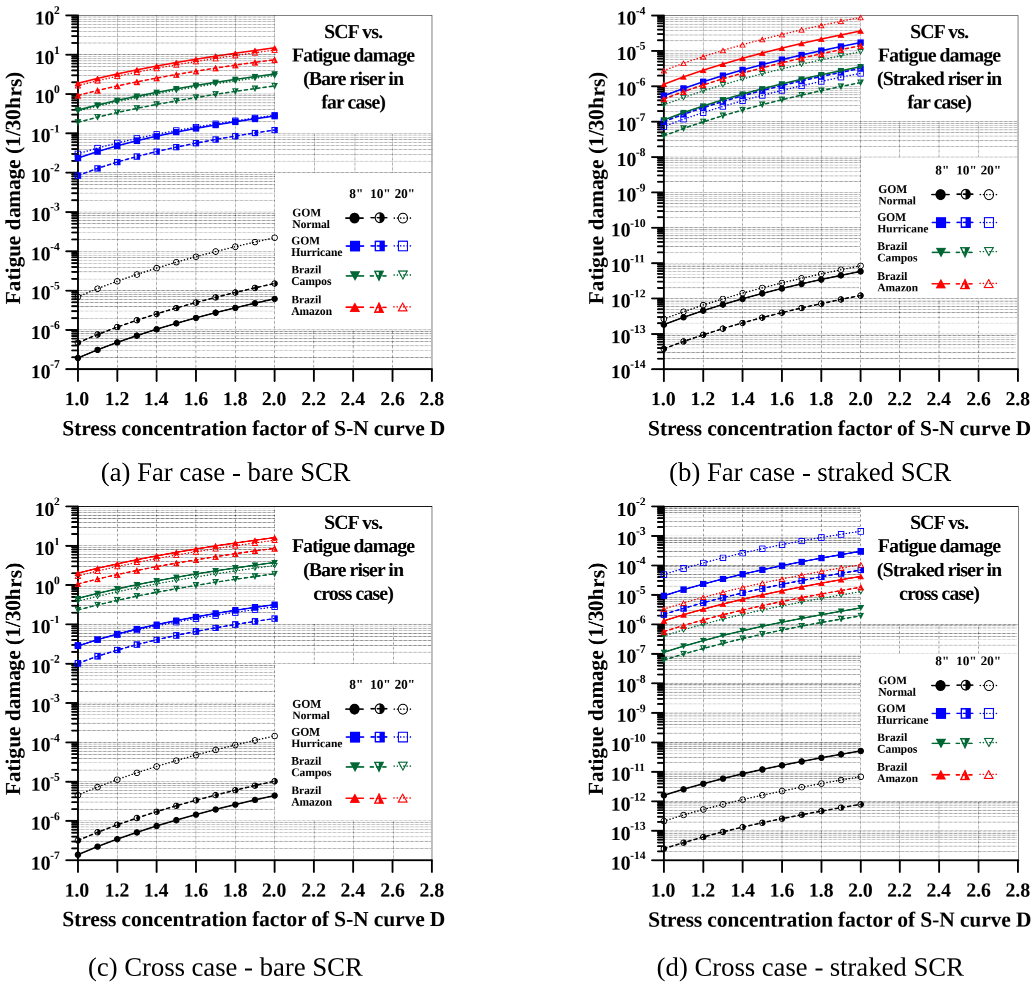
$$\alpha = \begin{cases} -5.014 & \text{for GOM Normal} \\ -4.972 & \text{for GOM Hurricane} \\ -5.000 & \text{for Brazil Amazon} \\ -5.002 & \text{for Brazil Campos} \end{cases} \quad (3.2)$$

The general relationship between S-N curve capacity and fatigue damage is expressed by Eq. (2). Current correction factor (α) was applied in order to investigate the effect of different current profiles. The obtained α based on the empirical formula is shown in Eq. (3.1) and (3.2). It was found that the range from -3.0 to -3.5 was applied to the general sea states except for GOM Normal case which shows around -5.0. It was clear that the four considered current shapes were not enough to draw a general trend. Instead, GOM fields are known as active and representative development regions for oil and gas production in the world, and the selected current profiles include various magnitudes that cover other sites as well. The difference of S-N curve capacity between F3 and others are calculated in Eq. (4). In case of straked SCR, the α was merged in near 5.0 range due to the strake effect.

$$C / C_{F3} = \begin{cases} 2.000 \text{ for } C1 \\ 1.428 \text{ for } E \\ 1.268 \text{ for } F \\ 1.125 \text{ for } F1 \\ 1.000 \text{ for } F3 \end{cases} \tag{4}$$

In case of D-type S-N curve, the results were not well-fitted with general trend line shown in Fig. 8 due to the different SCFs applied. The SCF range from 1.0 to 2.0 was considered in order to investigate the effect of SCF variation on VIV fatigue performance of SCRs.

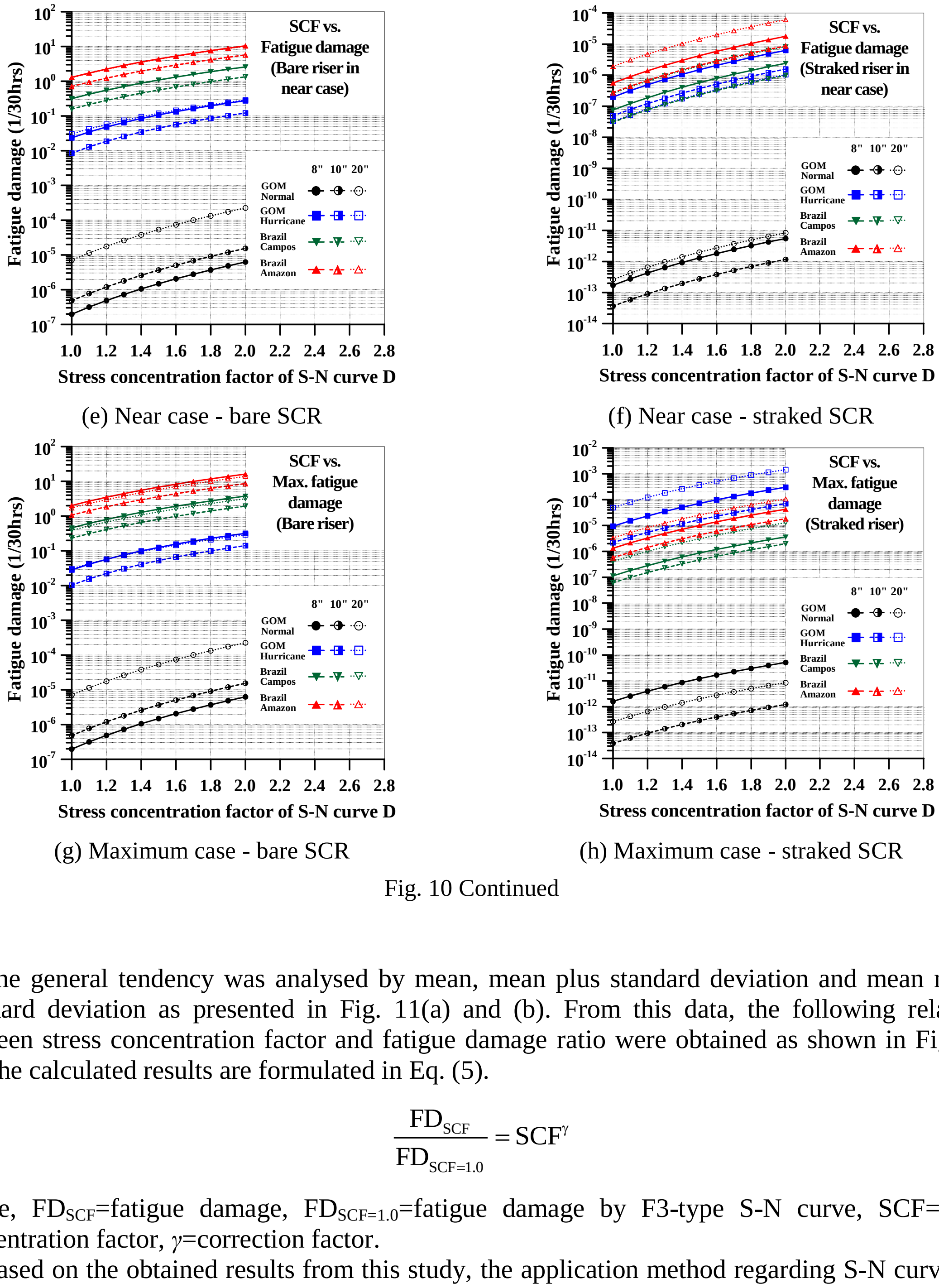
As SCF increased, it was observed that the fatigue damages increased as shown in Fig. 10. In contrast, fatigue life which has an inverse relationship could be decreased when the SCF increased. Based on these information in Figs. 10(a) to (h), the general tendency is deducted as shown in Figs. 11(a) and (b).



(a) Far case - bare SCR (b) Far case - straked SCR

(c) Cross case - bare SCR (d) Cross case - straked SCR

Fig. 10 Effect of stress concentration factor on VIV fatigue damage of SCRs



(e) Near case - bare SCR (f) Near case - straked SCR

(g) Maximum case - bare SCR (h) Maximum case - straked SCR

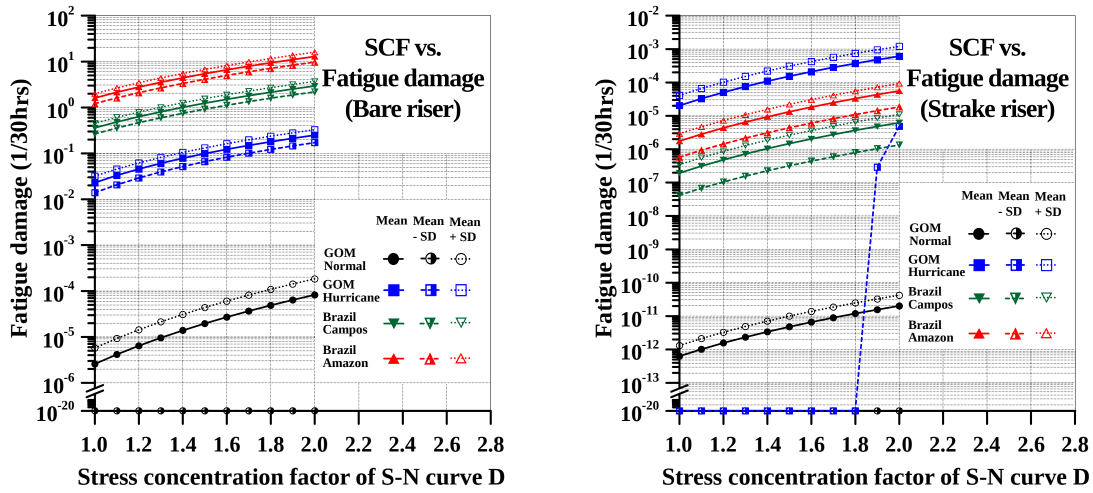
Fig. 10 Continued

The general tendency was analysed by mean, mean plus standard deviation and mean minus standard deviation as presented in Fig. 11(a) and (b). From this data, the following relations between stress concentration factor and fatigue damage ratio were obtained as shown in Fig. 12, and the calculated results are formulated in Eq. (5).

$$\frac{FD_{SCF}}{FD_{SCF=1.0}} = SCF^{\gamma} \tag{5}$$

where, FD_{SCF}=fatigue damage, $FD_{SCF=1.0}$=fatigue damage by F3-type S-N curve, SCF=stress concentration factor, γ=correction factor.

Based on the obtained results from this study, the application method regarding S-N curve and SCF effect was briefly summarized in order to estimate the fatigue performance of SCRs under short-term VIV effect. This study concerns about the abovementioned procedures between "riser fatigue analysis" and "selection of fatigue strength data" shown in Fig. 3. The riser designer should check the fatigue performance, once the design has been completed. It is also important to



(a) Bare SCR (b) Straked SCR

Fig. 11 Tendency of stress concentration factor and VIV fatigue damage of bare SCRs

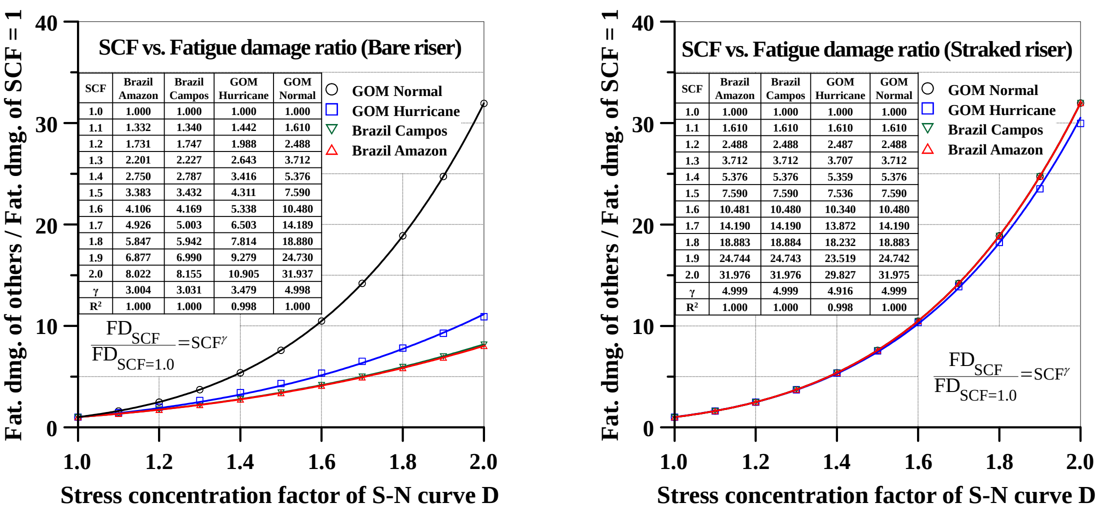
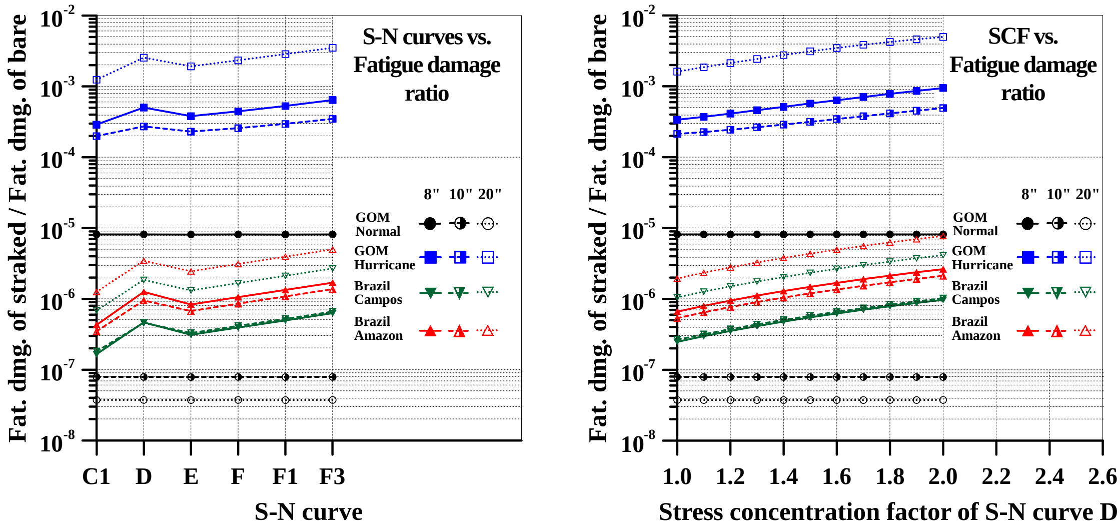


Fig. 12 Relationship between SCF and fatigue damage ratio for bare SCR

select the reasonable S-N curve that causes significant effect of deepwater riser's fatigue performance.

In this regard, the relationship between F3-type and other type of S-N curves was investigated in terms of fatigue damage and fatigue life due to the VIV. In case of D-type S-N curve, stress concentration factor (SCF) should be calculated based on Eq. (1). The SCF can be changed due to the riser's specification. SCF range from 1.0 to 2.0 is considered in order to investigate its effect on VIV fatigue performance of bare and straked SCRs. The designers can apply these results to the other SCR design project in order to estimate the S-N curve and SCF effects at the start point of fatigue design process.



(a) S-N curve (b) SCF

Fig. 13 Comparison of fatigue performance between bare and straked SCR under VIV

4.3 Discussions

Finally, comparison of fatigue performance between bare and straked SCR under short-term VIV have been performed as shown in Fig. 13. It is here shown that the effect of strake were observed as range of 10^{-4} to 10^{-3} for GOM Hurricane, 10^{-7} to 10^{-5} for GOM Normal, 10^{-7} to 10^{-5} for Brazil Amazon and Campos. When the small current is applied to the SCR, the fatigue damage ratio between bare and straked SCR shows linear relationship.

5. Conclusions

In the present study, two results regarding VIV effect on fatigue performance of SCRs were obtained. The first one was the relationship between S-N curve type about hollow section and VIV fatigue performance of SCRs. The other was the effect of SCF on VIV fatigue performance of SCRs. Two types of SCRs, i.e., production and export riser, and three types of SCR specifications, i.e., 8-inch (production), 10-inch (production) and 20-inch (export) were considered to identify the general tendency regarding the effect of S-N curve type and SCF. In addition, bare and straked cases of SCR were adopted. In this study, DNV (2012) guideline was only considered for the selection of the S-N curve, but other codes such as American Petroleum Institute (API), British Standards (BS), and many others may also be applied in further studies.

The obtained results can be summarized as follows.

1. Based on the fatigue analysis results, the relationship between fatigue damage and structural capacity by each S-N curve was determined and an empirical formula was proposed ($FD/FD_{F3}=(C/C_{F3})^{\alpha}$). Specifically, the left term is made up of the ratio of fatigue damage (FD), fatigue damage by F3-type S-N curve (FD_{F3}), and right term is composed of the ratio of fatigue resistance capacity (C), fatigue resistance capacity of F3 type S-N curve (C_{F3}).

2. The current correction factor (α) for bare SCR was calculated and obtained for four selected current conditions, i.e., −4.998 for GOM normal, −3.504 for GOM Hurricane, −3.030 for Brazil Amazon and −3.302 for Brazil Campos. It was found that the range between −3.3 to −3.6 can be applied to the GOM and Brazil sea states except for unique case such as Hurricane. In case of straked SCR, −5.0 could cover the applied four different areas.

3. The relationship between fatigue resistance capacity (C) and fatigue resistance capacity of F3 type S-N curve (C_{F3}) was determined. It was found that the ratios of C/C_{F3} were 1.125 for F1-type, 1.268 for F-type, 1.426 for E-type, 2.0 for C1-type and 2.856 for B2-type S-N curve.

4. The SCF ranges of 1.0 to 2.0 were considered to identify SCF effect on VIV fatigue performance of SCRs. Based on the calculated fatigue performance, the effect of SCF on fatigue damage and fatigue life of SCRs was identified. In addition, effect of strake on SCR under short-term VIV has been investigated. However, additional benchmarking study should be performed and it should produce better results.

Through the present study, the SCR designer could estimate fatigue damage based on each type of S-N curve and it will be helpful to choose optimized design curve. Finally, three limited types of SCRs, i.e., 8-inch, 10-inch, and 20-inch, were applied to this study. In order to draw a generalized result in terms of fatigue performance under vortex-induced vibration, different types of SCRs should be considered for further study.

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