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SHORT-TERM FATIGUE DAMAGE OF TETHERS OF LONG-SPAN FLOATING CABLE SUPPORTED BRIDGES UNDER HARSH WAVES

Deokhee Won[1], Keesei Lee[2], Young-Jong Kang[3], and Seungjun Kim[3]

Key words: loating cable supported bridges, hydrodynamic analysis, tethers, fatigue.

ABSTRACT

A floating bridge can be effectively used for sea-crossing in deep water. Because the superstructure of the bridge is supported by floating substructures with pontoons, the conventional fixed piers, towers, foundations, and piles are not required. Instead, a rational mooring system can be used to strictly maintain the target position of the floating substructures against environmental loads, including winds, waves, and currents. Recently, long-span cable-supported bridges with floating towers were investigated and found to overcome the limitations of conventional cable-supported bridges, when used as sea-crossing infrastructure. To design the moorings for very large floating structures, the structural safety should be carefully investigated. In addition to the maximum stress, fatigue damage should also be studied. This study aims to investigate the characteristics of the short-term fatigue damage accumulated at sections of the tethers in long-span cable-supported bridges under harsh wave conditions. To evaluate the accumulated fatigue damage due to waves, the Palmgren–Miner rule is used, wherein the time-series wave-induced stresses acting on sections of the tethers are analyzed using the rainflow counting method. The wave-induced stresses are obtained by conducting time-series hydrodynamic analyses for a floating-bridge model, using ABAQUS AQUA. An irregular wave with 100-year return period, modeled by JONSWAP wave spectrum, is applied to the structure. The effects of the floater type, draft, and initial tether inclination on the fatigue damage are summarized after intensive parametric studies.

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I. INTRODUCTION

Conventional bridges have been widely used for sea-crossing transportation infrastructures owing to their structural reliability. However, their applicability is limited by environmental conditions, especially, the water depth. Moreover, the construction of extremely high columns and piers in deep waters is quite challenging. In addition to the constructability, the structural stability of high-rise compressive members is also a critical issue in the design and construction of bridges in deep water. Thus, alternative transportation systems such as floating bridges and submerged floating tunnels (SFTs) have been suggested by many researchers who studied the feasible conceptual models (Martire, 2010; Østlid, 2010; Norwegian Public Roads Administration, 2011; Ellevset, 2014; Villoria et al., 2017a), static and dynamic structural behaviors of floating bridges (Dørum et al., 2017; Papinutti et al. 2017a; Villoria et al., 2017b) and SFTs (Kunisu et al., 1994; Remseth et al., 1999; Pilato et al., 2008; Won and Kim, 2018; Won et al., 2019), and effective analysis methods (Cifuentes et al., 2015; Papinutti et al., 2017a; Papinutti et al., 2017b).

Unlike SFTs, floating bridges have been constructed in several countries such as Norway, the United States, and Canada. Although a long-span floating bridge has not yet been constructed, the static and dynamic behavioral characteristics of long-span cable-supported bridges with floating towers have been continuously studied.

Villoria et al. (2017a) introduced the concept of a multispan suspension bridge on a floating foundation. Villoria et al. (2017b) studied the stability of floating cable-supported bridges subjected to winds and waves during operation and concluded that long-span floating bridges could be applied in Norwegian environments under 100-year-return-period conditions. Papinutti et al. (2017a) studied the dynamic characteristics of floating suspension bridges moored by tensioned tethers under wind and wave loading and performed time-domain hydrodynamic analyses. Papinutti et al. (2017b) also suggested a frequency-domain analysis method for a similar type of floating bridge. Dørum et al. (2017) studied the behavioral characteristics of floating suspension bridges upon

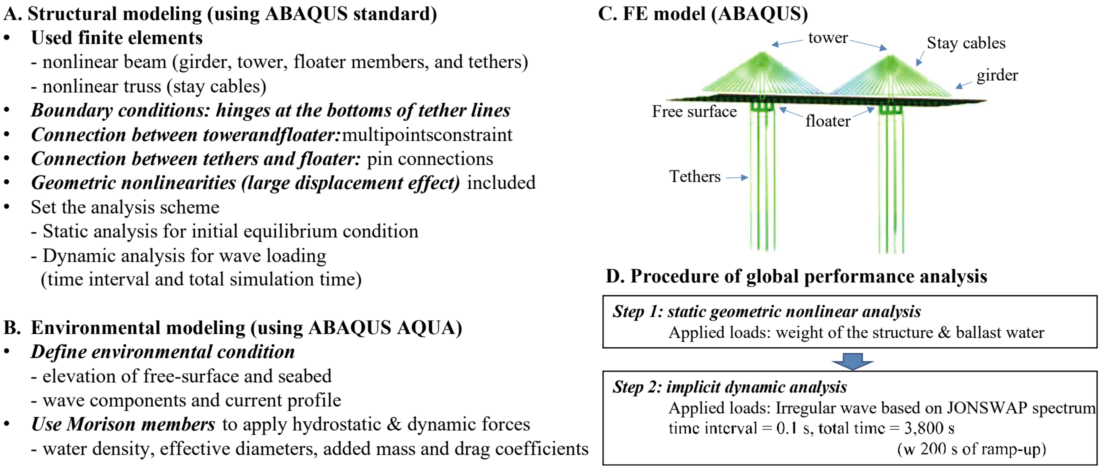


Fig. 1. Strategy for global performance analysis

ship impact. Xu et al. (2018a) studied the rational simulation method for investigating the dynamic responses of the long-span floating cable supported bridges under the wind and wave loadings in time-domain. Xu et al. (2018b) studied the long-term dynamic behaviors of the long-span floating bridges under the extreme environmental conditions. Jang et al. (2020) investigated the effects of the geometric design parameters on the static structural state under the vertical loadings and suggested the primary design strategy for securing the target deformation shape of the floating cable supported bridges.

The structural stability and serviceability of the long-span floating bridges are determined by their mooring design. Because floating bridges are designed and constructed as transportation infrastructure, structural responses of the bridges under environmental loading conditions should be strictly limited. For enhancing the structural safety and reliability, the moorings should be designed with sufficient fatigue life as well as structural strength.

This study aims to investigate the characteristics of the short-term fatigue damage accumulated at sections of the tethers of long-span cable-supported bridges under harsh wave conditions. The short-term fatigue damage evaluation is conducted using the Palmgren–Miner rule, where the time-series fluctuating stresses of the tethers due to the applied waves are calculated. To obtain the stresses, a global performance analysis based on hydrodynamics is conducted using the ABAQUS program (Simulia Inc, 2019). For simulating the harsh wave conditions, a 100-year return period irregular wave is modeled using the JONSWAP wave spectrum. By conducting a parametric study, the effects of the floater type, draft, and initial tether inclination on the fatigue damage are studied and summarized.

II. THEORETICAL BACKGROUND AND SIMULATION STRATEGY

1. Equation of motion of submerged rods

In general, hydrodynamic loads acting on the submerged structural members are calculated based on the potential flow theory. However, it is well known that the Morison equation can be used to calculate hydrodynamic loads acting on submerged members whose diameter-to-wavelength ratios are less than 1/5 (Xu et al., 2019). In this study, the Morison's equation is used to calculate the hydrodynamic force per unit length acting on the submerged moving parts including floater and tethers shown in Eq. (1).

$$\begin{aligned} F^d &= \rho A_I \dot{V}^n + C_A \rho A_I (\dot{V}^n - \ddot{r}^n) + \frac{1}{2} C_D \rho D \left| V^n - \dot{r}^n \right| \left(V^n - \dot{r}^n \right) \\ &= -C_A \rho A_I \ddot{r}^n + C_M \rho A_I \dot{V}^n + \frac{1}{2} C_D \rho D \left| V^n - \dot{r}^n \right| \left(V^n - \dot{r}^n \right) \end{aligned} \tag{1}$$

The force q_n acting to the submerged members, including both static and dynamic components, is summarized below:

$$\begin{aligned} q_n = w + F^s + F^d &= w + B - \left(P A_I r' \right)' - C_A \rho A_I \ddot{r}^n \\ &+ C_M \rho A_I \dot{V}^n + \frac{1}{2} C_D \rho A_D \left| V^n - \dot{r}^n \right| \left(V^n - \dot{r}^n \right), \end{aligned} \tag{2}$$

where w is the weight per unit length; F^s is the hydrostatic force per unit length; F^d is the hydrodynamic force per unit length; B is the buoyancy force per unit length; P is the hydrostatic pressure; C_I is the inertia coefficient; C_D is the drag coefficient; C_M is the mass coefficient = C_A+1; C_A is the added mass coefficient; $\dot{r}^n$ and $\ddot{r}^n$ are the normal structural velocity and acceleration of the rod, respectively; V^n and $\dot{V}^n$ are the normal velocity and acceleration of water, respectively; ρ is the fluid density, and A_D is the cross-sectional area of the rod projected on a plane normal to the centerline of the rod.

Table 1. General properties of the main members of the bridge model

	Girder	Tower	Stay cables	Tendons
EA (kN)	1.58E8	1.57E8	2.10E6	7.65E6
EI, in-plane (kN·m^2)	3.04E8	1.32E9	-	3.22E5
EI, out-of-plane (kN·m^2)	5.76E9	6.91E10	-	3.22E5
Unit weight (kN/m^3)	77.01	77.01	77.01	77.01

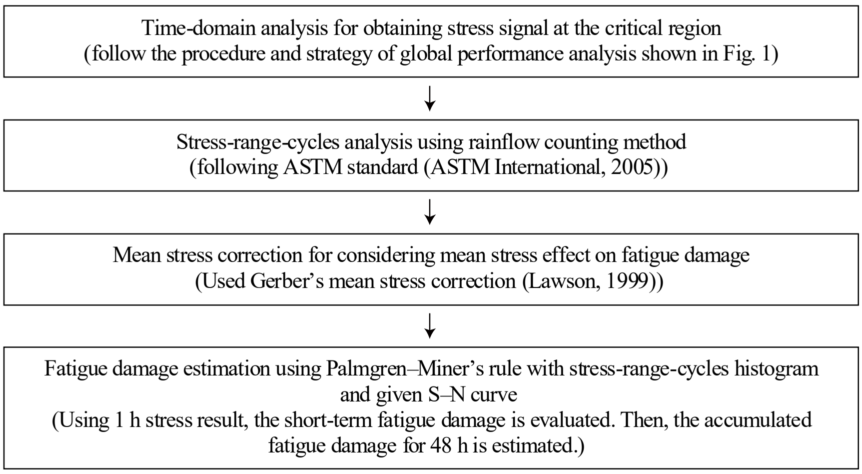


Fig. 2. Procedure of short-term fatigue damage calculation

2. Global performance analysis of floating cable-supported bridges under wave conditions

To obtain the wave-induced stresses for fatigue damage calculation, a global performance analysis of the examined floating cable-supported bridges is conducted, considering the wave-induced hydrodynamic loads. As mentioned in Section II.1, a semiempirical approach using the Morison's equation is followed because of the dimensions of the floating members. Moreover, a time-domain analysis is performed to consider the various geometric nonlinearities of the floating cable-supported bridges, such as the tether–floating tower–stay cable–girder interactions, sag effects of stay cables and tethers, and large displacement effects. Fig. 1 shows the simulation strategy for the time-domain global performance analysis of the floating bridges. As shown in the figure, the girder, tower, floater members, and tethers were modeled by 6 degrees of freedoms nonlinear beam elements while the stay cables were modeled by 3 degrees of freedoms nonlinear truss elements. When the heave motion of the floating bridges occurs, the tension of the tethers would be significantly changed. Therefore, the sag effect of the tethers should be taken into account. So, the 5.0 m long nonlinear beam elements were used to model a tether for considering the sag effect as well as the flexural stiffness.

3. Fatigue design criterion for tethers of floating structures

Considering API RP 2T (American Petroleum Institute, 2010), the short-term fatigue design criterion for a tether of a floating bridge are assumed. In this study, the short-term fatigue damage accumulated for 48 h, induced by a 100-year return-period wave, is assumed to not exceed 0.01.

4. Procedure of short-term fatigue-damage estimation under specified wave conditions

The short-term fatigue damage accumulated at the sections of the tethers, induced by a specified wave, is estimated by the procedure shown in Fig. 2. If a stress acts on a section, due to a wave, the fluctuating stress ranges and their cycles are counted by the rainflow counting method. Then, the stress-range-cycle histogram is obtained, and the accumulated fatigue damage can be calculated based on the Palmgren–Miner's rule with a given S–N curve. In this study, the S-N curve presented by DNV RP C203 (S-N curves in seawater with cathodic protection) is used (Det Norske Veritas, 2011). The stress concentrate factor (SCF) is calculated following the DNV procedure, considering the dimensions of the tether section (Det Norske Veritas, 2011). The evaluated SCF is 1.25, and the time-series stress obtained by global performance analysis is multiplied by the SCF and the corrected stress is considered.

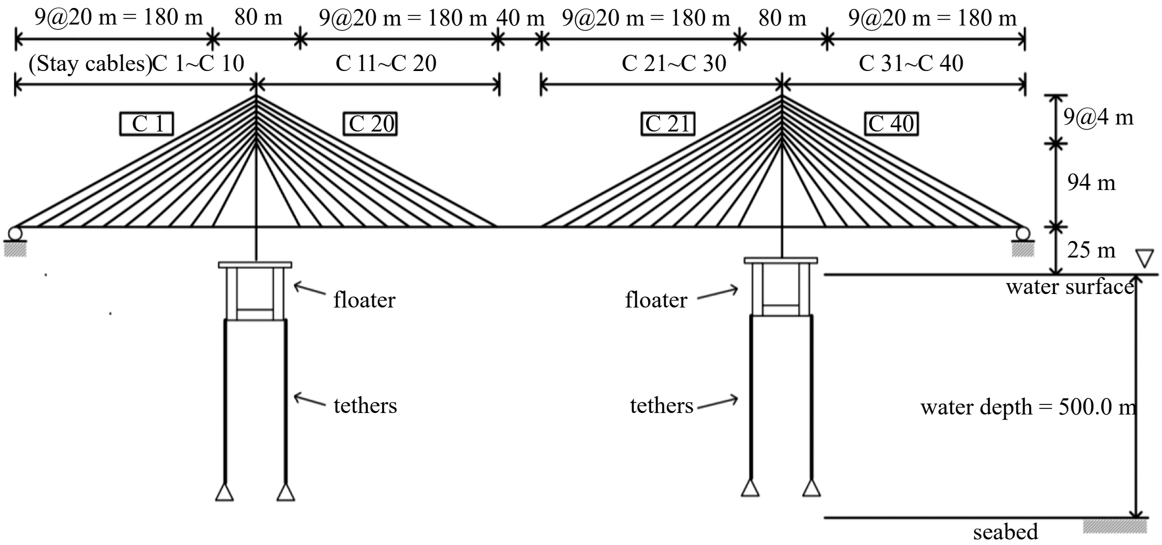


Fig. 3. Examined floating cable-supported bridge.

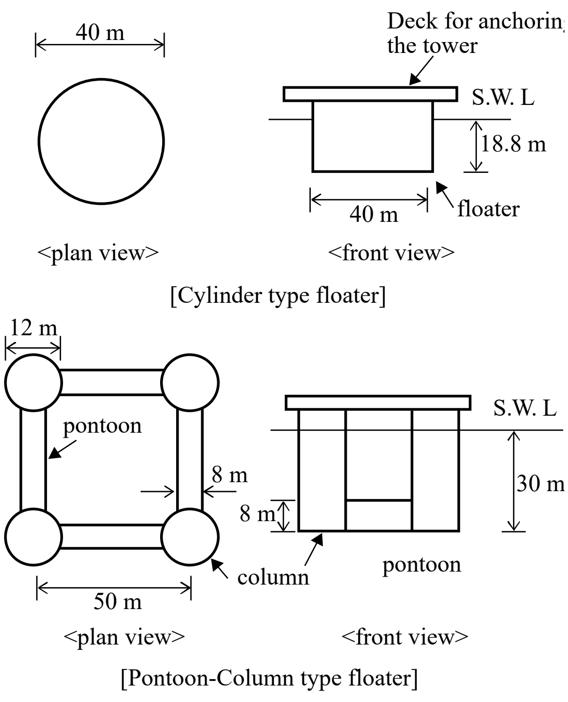


Fig. 4. Examined floating cable-supported bridge.

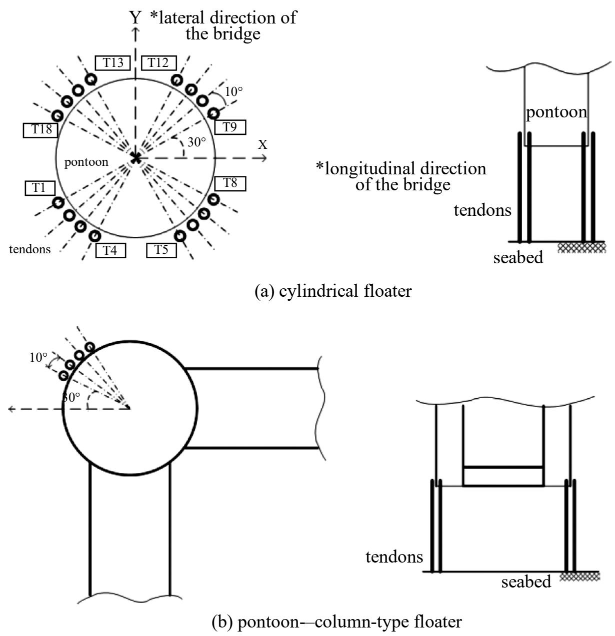


Fig. 5. Tether arrangement for each floater type.

III. SHORT-TERM FATIGUE DAMAGE TO TETHERS UNDER HARSH WAVES

1. Analysis model and environmental conditions

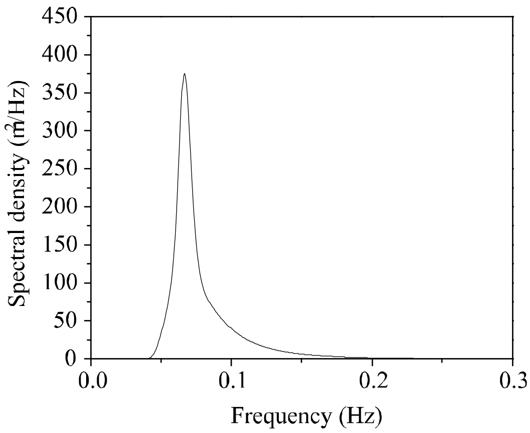
As shown in Fig. 3, a 920.0 m long floating cable-supported bridge is simulated to investigate the dynamic behavior under severe wave conditions. The superstructure is supported by 80 stay cables and the cables are anchored to the floating towers. The towers are settled to the floaters. The positions of the floaters are controlled by tethers anchored to the seabed. In this study, two different types of floaters are considered—a simple cylindrical type and a pontoon–column type—as shown in Fig. 4. Fig. 5 shows the considered floater types with tether arrangements. As shown in the figure, 16 steel pipe-type tethers whose outer diameter and wall thickness are 0.6 and 0.02 m, respectively, are attached. The material properties are the same as those of API X70 grade. Table 1 shows the general properties of the main structural members. For global performance analysis, the drag coefficient and added mass coefficient of the circular sections of the tethers, submerged cylinder, and columns of floaters are 1.2 and 1.0, respectively, whereas

Table 2. Comparison of natural frequencies of the models with different floater types

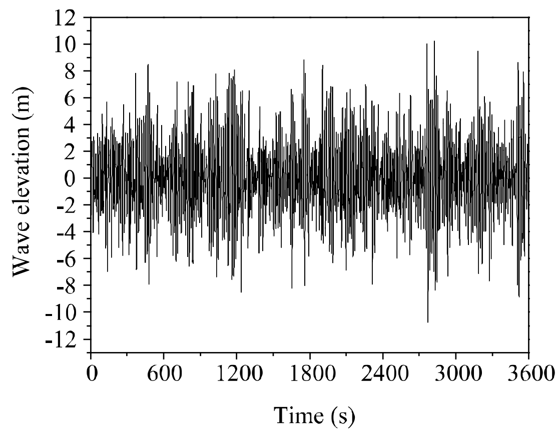
	w cylinder type floater	w pontoon-column type
1st mode	1.63E-2 Hz (61.3 sec), Lateral motion	1.62E-2 Hz (61.7 sec), Lateral motion
2nd mode	4.79E-2 Hz (20.9 sec), Lateral motion	4.80E-2 Hz (20.8 sec), Lateral motion
3rd mode	1.82E-1 Hz (5.5 sec), Vertical motion	2.04E-1 Hz (4.9 sec), Vertical motion
4th mode	1.84E-1 Hz (5.4 sec), Vertical motion	2.07E-1 Hz (4.8 sec), Vertical motion

Table 3. Displacements of the floating bridges with different types of floaters.

	with cylindrical floater		with pontoon–column-type floater	
	Lateral displ.	Vertical displ.	Lateral displ.	Vertical displ.
Min (m)	−14.63	−1.86	−3.80	−0.09
Max (m)	18.60	0.52	4.67	0.08
Average (m)	0.26	-0.04	0.02	0.00
Standard deviation (m)	4.58	0.18	1.26	0.03

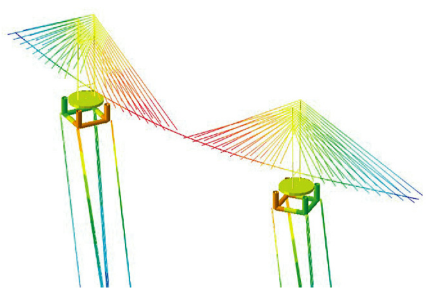


(a) spectral energy density

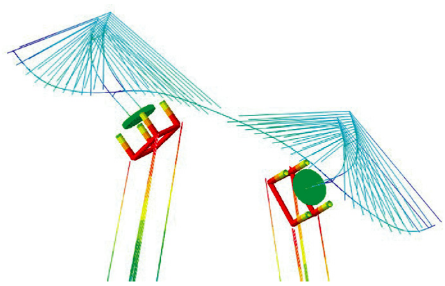


(b) time-series wave elevation

Fig. 6. Applied wave conditions generated by JONSWAP wave spectrum with H_s=11.32 m, T_p=15.1 s, and γ =3.3.



(a) symmetric lateral mode (natural period = 61.7 sec)



(b) symmetric vertical mode (natural period = 4.8 sec)

Fig. 7. Free vibration mode of the floating cable supported bridge with pontoon-column type floater

that of the rectangular-section pontoons are 2.1 and 1.51, respectively.

The global performance analysis is conducted following the procedure shown in Fig. 1. In a static analysis step, the weights of the main members (girder, slab, tower, stay cables, floater, and tethers) and ballast water, buoyancy, and traffic load are

Table. 4 Dimensions of columns used in the case study.

Types	30.0 m draft model	36.0 m draft model	42.0 m draft model
Length (m)	30.0	36.0	42.0
Diameter (m)	12.0	11.0	10.0

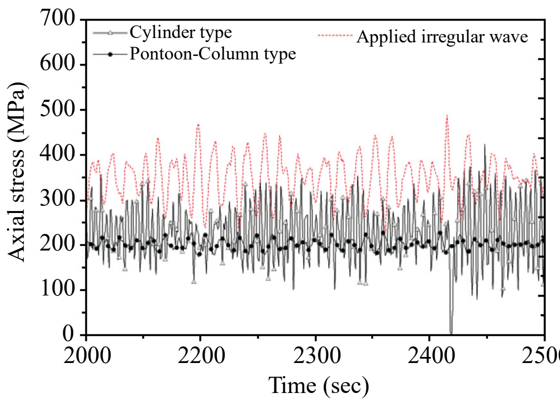


Fig. 8. Stress at the section of a tether of a floating bridge with different types of floaters.

applied. After finding the force-equilibrium for the static loading condition, implicit dynamic analysis is conducted under the wave-loading condition for 3800 s.

Fig. 6. shows the applied 100-year return-period wave whose peak period and significant wave height are 15.1 s and 11.32 m, respectively. These wave conditions have been used in a previous study for developing the offshore renewable energy facilities in the southern part of Korea (Son et al., 2015). The irregular wave model is generated using a JONSWAP wave spectrum.

Before conducting global performance analysis, the natural vibration modes and frequencies of the models with different floaters were analzed and compared shown in Fig. 7 and Table 2. Because the total mass was fitted with each other, there are no significant differences in the mode shapes and frequencies of free vibration. According to the frequency analysis results, the natural periods of the models were not close to the peak period of the examined wave. It means that the numerical models were properly designed avoiding the resonance.

2. Effects of the floater type on the short-term fatigue damage

As shown in Fig. 8, the fluctuating stress on the tethers, induced by the irregular wave, depends on the type of the floater. According to the analytical results, a pontoon–column-type floater can be used for reducing the dynamic response of the floating bridge. Table 3 shows the statistical values of the wave-induced displacements of the models with different floaters.

The decrease in the displacements of the floating structure are due to the reduction of the wave-induced hydrodynamic force. The floaters under comparison are designed with same volume; therefore, the drafts of the cylindrical and pontoon–column-type floaters are 18.8 and 30.0 m, respectively. An increase in the draft leads to a decrease in the wave-induced force, although similar maximum waterplane areas are applied. Consequently, the stress in the tethers are expected to be mitigated by the application of the pontoon–column-type floater instead of a single cylindrical floater.

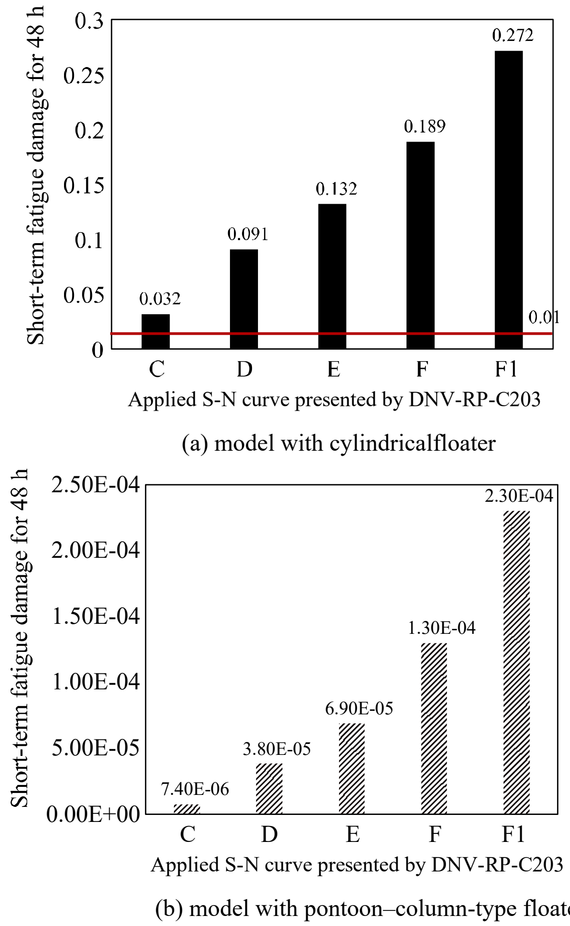


Fig. 9. Short-term fatigue damage due to harsh wave conditions for 48 h

Fig. 9 clearly shows the effects of the floater type on the short-term fatigue damage to the tethers under harsh wave conditions. Because of the mitigation of the wave-induced motion of the floating tower, the short-term fatigue damage to the tethers can be reduced effectively. According to the analytical results, all the cases of the the case with the F1 S-N curve, whereas, all cases of the model with cylindrical floaters may not be able to satisfy the criterion.

3. Effect of the draft of the floater on short-term fatigue damage

Owing to the effect of the draft of the floater on the mitigation of the dynamic responses induced by wave forces, the deep-draft design is expected to be effective for mitigating the fatigue damage to the tethers. In this study, case studies

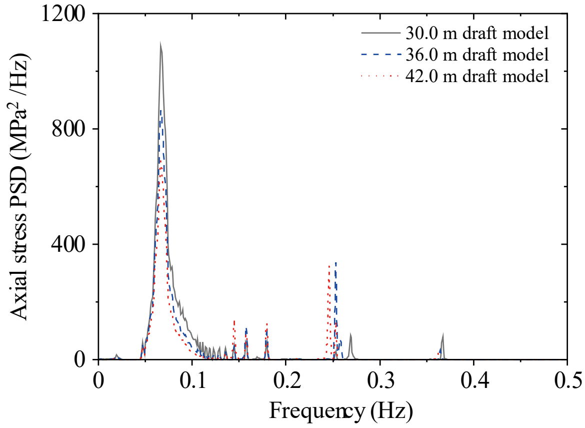


Fig. 10. Power spectral densities of tether stresses of different draft models.

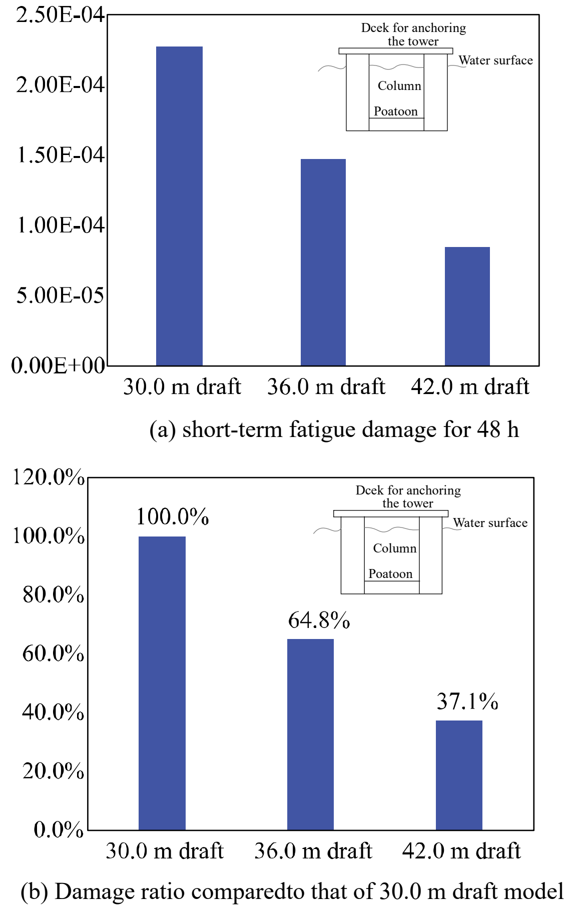


Fig. 11. Effect of the floater draft on short-term fatigue damage to tethers.

to investigate the effect of the floater draft on the mitigation of the stresses of the tethers are conducted with three different dimensions of the floaters, shown in Table 4.

Figs. 10 and 11 clearly show the effect of the floater draft on the stress and short-term fatigue damage to the tethers, respectively. According to the analytical study, when a 42.0 m

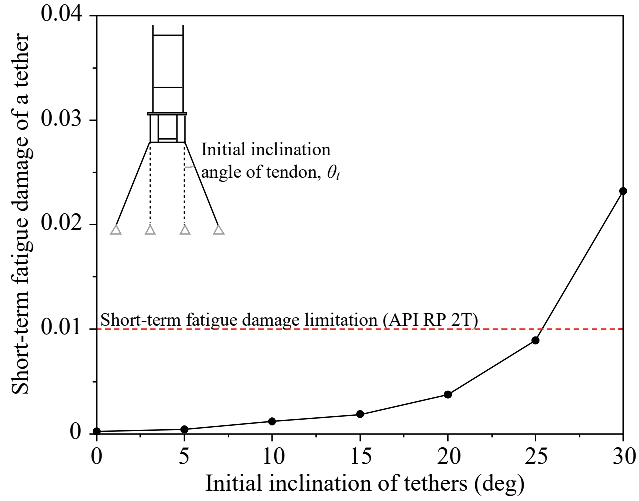


Fig. 12. Effect of initial tether inclination on the short-term fatigue damage.

deep-draft pontoon–column-type floater is used, the fatigue damage is reduced dramatically by 62.9 %, when compared to the damage of a 30.0 m draft floater model. Despite this, it should be assumed that, as a deep-draft column is used, the structural stability of the column, such as the buckling of the member and constructability of the floater, should be checked carefully.

4. Effect of initial tether inclination on short-term fatigue damage

The initial inclination of the tethers affects the static stiffness of the floating tower. If the inclination is designed to be large, the lateral directional component of the induced stiffness will increase and the vertical directional component of the stiffness will decrease. Thus, the initial inclination of the tether has positive and negative effects on the motion of the floater. Fig. 12 shows the tendency of the short-term fatigue damage to the tethers with change in the initial inclination. According to the analytical results, the fatigue damage is greater if the initial inclination is large. The initial inclination of the tethers should be studied intensively to minimize the motion of the floating transportation systems. The inclination should be determined considering the fatigue damage criteria as well. In this study, the model was designed with the initial inclination of the tethers not exceeding 25°.

IV. CONCLUSIONS

The characteristics of short-term fatigue damage accumulated at the tethers were investigated through a global performance analysis based on hydrodynamics. To find the practical design strategy for long-span floating cable-supported bridges, parametric studies were conducted considering the floater types, floater drafts, and initial inclination of tethers. The conclusions of this analytical study are presented below:

A. For mitigating the dynamic responses induced by wave forces, pontoon–column-type floaters were found to be more appropriate than the simple single-cylinder–type floater. By using four smaller-section columns instead of a large-diameter single cylinder, the floater draft could be enlarged so the wave force that induced the dynamic response could be reduced effectively.
B. A deep-draft design was found to be effective for mitigating the short-term fatigue damage to the tethers under harsh environmental loads. According to the analytical results, 36.0 and 42.0 m draft models showed 64.8 and 37.1 % tether fatigue damage, when compared to the 30 m draft model. Nevertheless, more intensive studies should be conducted to investigate the optimum draft of the floater, considering the constructability and structural stability of the columns.
C. The initial inclination of the tethers directly affected the horizontal and vertical static stiffnesses of the floating towers. Therefore, investigating the optimum initial inclination of the tethers is important for mitigating the dynamic response of the floating structures. Unfortunately, the short-term fatigue damage induced by wave forces increases as the inclination of the tethers increases. Therefore, the engineers should determine an optimum inclination of tethers, which can minimize the displacement, considering the limitations of short-term fatigue damage criteria.

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