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DYNAMIC BEHAVIOR OF A LONG-SPAN CABLE-STAYED BRIDGE WITH FLOATING TOWERS AFTER THE SUDDEN FAILURE OF TETHERS AND CABLES UNDER IRREGULAR WAVES

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Key words: floating cable-stayed bridge, sudden failure analysis, tether arrangement, irregular wave.

ABSTRACT

Cable-supported bridges with floating towers do not require fixed piers at the seabed. Therefore, innovative conceptual models have been continuously developed to overcome the limitations of conventional bridges in deep waters. The main floating tower that supports superstructures using stay cables is balanced by the buoyancy of floaters moored by tethers. The applicability of floating bridges should be verified by evaluating the overall stability considering the tether design. Here, various cases of the sudden failure of tethers and stay cables under the environmental conditions of a 100-year return period are simulated in a time-domain. The floating cable-stayed bridges are subjected to constantly changing environmental loads such as wind, waves, and current. The dynamic analysis of these loads was performed, applying the irregular wave load generated by the Joint North Sea Wave Project (JONSWAP) spectrum model. The structural responses of the floating bridges were evaluated via hydrodynamic analysis after the sudden failure was simulated. In this study, various cases were evaluated considering the number of failed tethers and stay cables. When the four tethers suddenly failed in the 100-year return period wave conditions, some of them exhibited structural stress exceeding the yield stress, and others even suffered compression. The effects of the sudden failure of the tethers and stay cables on the change in structural responses and states were directly compared in an intensive parametric study. According to the analytical study, the sudden failure of the tethers induces a significant increase in the dynamic responses of the floating bridges.

I. INTRODUCTION

Conventional marine bridges have been widely used as sea-crossing transportation infrastructure because of their sufficient reliability and verification. However, they are limited by environmental conditions, especially in deep waters. Additionally, the constructability and structural stability of the high-rise compressive members are critical issues in the design and construction of the bridge in deep waters. To address these issues, many researchers have proposed floating bridges or submerged floating tunnels (SFTs) as new alternative transportation structures. Feasible concepts (Martire, 2010; Østlid, 2010; Norwegian Public Roads Administration, 2011; Ellevset, 2014; Villoria et al., 2017a), static and dynamic behaviors of floating bridges (Cheng et al., 2020; Dai et al., 2020; Dørum et al., 2017; Jin and Kim, 2017; Papinutti et al., 2017a; Villoria et al., 2017b) and submerged floating tunnels (Kunisu et al., 1994; Remseth et al., 1999; Pilato et al., 2008; Won and Kim, 2018; Won et al., 2019), as well as effective analysis methods (Cifuentes et al., 2015; Papinutti et al., 2017a; Papinutti et al., 2017b) have been studied. Unlike SFTs, which have never been built, floating bridges have been built in many countries, such as Norway and the United States. Thus far, a long-span floating bridge has not yet been built; however, studies on long-span floating bridges have been carried out continuously and have a high possibility of realization.

Papinutti et al.(2017a) used time-domain tools to analyze the coupled wind and wave load responses of a long-span floating suspension bridge. For the initial screening analysis, a frequency-domain analysis was conducted to evaluate the critical combination of the wind events of a TLP suspension bridge (Papinutti et al., 2017b). The floating suspension bridge model was examined in a study on the E39 project in Norway, and the environmental conditions in the E39 region were found to be relatively mild. Kim et al. (2018) presented an overview of the main hydrodynamic analysis techniques for cable-supported bridges with floating towers. Jang et al. (2020) evaluated the effects of the various geometric parameters on

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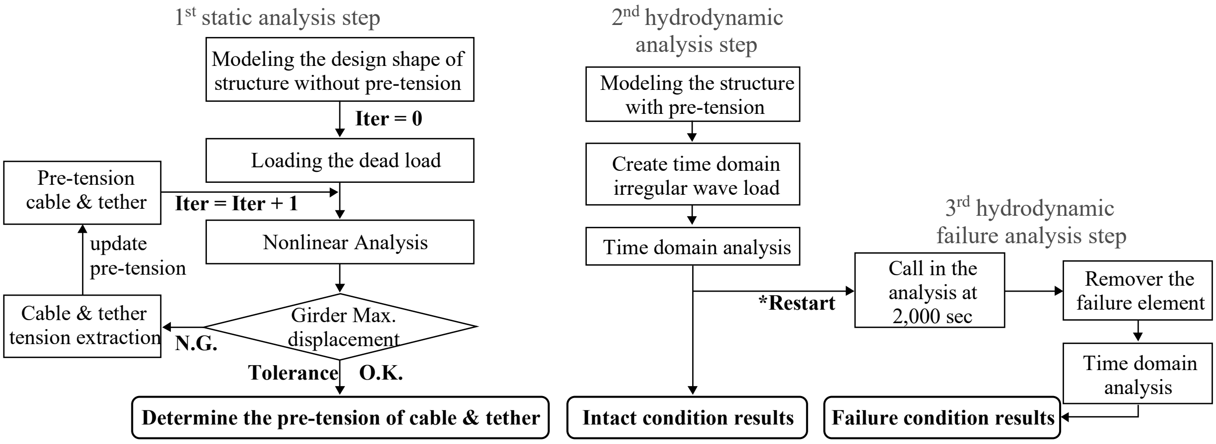


Fig. 1. Sudden failure analysis procedure

the static structural state under the dead load and suggested the primary design strategy of the floating cable bridges. Kim et al. (2019) studied the short-term fatigue of a tether with various tether slopes, under severe environmental conditions.

Structural stability and safety are mainly determined by the design of the tether moored to the main tower of the floating cable bridge. Unfortunately, owing to tether's replacement or sudden failure that dominates the overall behavior of floating cable bridges, these structures have not yet been evaluated in detail, although the behavior of the conventional cable-stayed bridge, which is affected by stay cable failure has been studied (Kim and Kang, 2016).

In this study, the dynamic behavior of a floating cable-stayed bridge after the sudden failure of a tether or cable was evaluated under a 100-year return period irregular wave loading. To evaluate the dynamic behavior, hydrodynamic finite element analysis was performed using ABAQUS AQUA (Simulia Inc, 2019), and a JONSWAP wave spectrum model was used to simulate the extreme irregular wave conditions of the 100-year return period.

II. THEORETICAL BACKGROUND AND SIMULATION STRATEGY

1. Equation of motion of the submerged rods

The hydrodynamic wave load acting on a submerged structure is calculated based on the circular motion of water particles from the wave. The load generated by the circular motion of the water particles is calculated using the wave potential theory and reflects the characteristic values according to the frequency domain of the structure. However, the hydrodynamic wave load can be calculated by simply using the Morison equation, which provides the wave load acting on a line element having a smaller area than the wavelength (Xu et al., 2019). In this study, the hydrodynamic environmental load acting on the submerged floaters and tethers is calculated using Morison's equation shown in Eq. (1).

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

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

where q_n = force acting on the submerged member, w = weight per unit length, F^s = hydrostatic force per unit length, F^d = hydrodynamic force per unit length, C_I = inertia coefficient, C_D = drag coefficient, C_M = mass coefficient = $C_A + 1$, C_A = 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 the water particle, respectively, ρ = fluid density, A_I = cross sectional area normal to centerline of the rod, and A_D = cross sectional area of the rod projected to a plane normal to the centerline of the rod.

2. Procedure of sudden failure analysis of tethers and stay cables for floating cable-stayed bridges under irregular waves

Cables experience tensile stress only when tensile strain occurs; those in cable bridges require large tensile forces to support the superstructure. Therefore, if initial tension is not applied, the state of the cable is different from the shape of the initially designed structure, until the cable creates a tension that balances the force with the superstructure. The initial shape analysis of the cable bridge is essential for calculating and applying the appropriate initial tensile forces. In this study, because the tethers mooring the floater of the floating cable bridge have similar mechanisms, the initial shape analysis of

Table 1. Section properties of the main members

	Section area A (m^2)	2nd moment of inertia I (m^4)	Unit weight γ (kN/m^3)	Compressible	Modulus of elasticity E (N/m^2)	Yielding σ_y (Mpa)
Girder	0.75	1.45	77.01	Y	2.1×10^{11}	355
Tower	0.37	3.14	77.01	Y	2.1×10^{11}	355
Cable	0.01	-	77.01	N	2.1×10^{11}	1800
Tether	0.0364	-	77.01	N	2.1×10^{11}	448

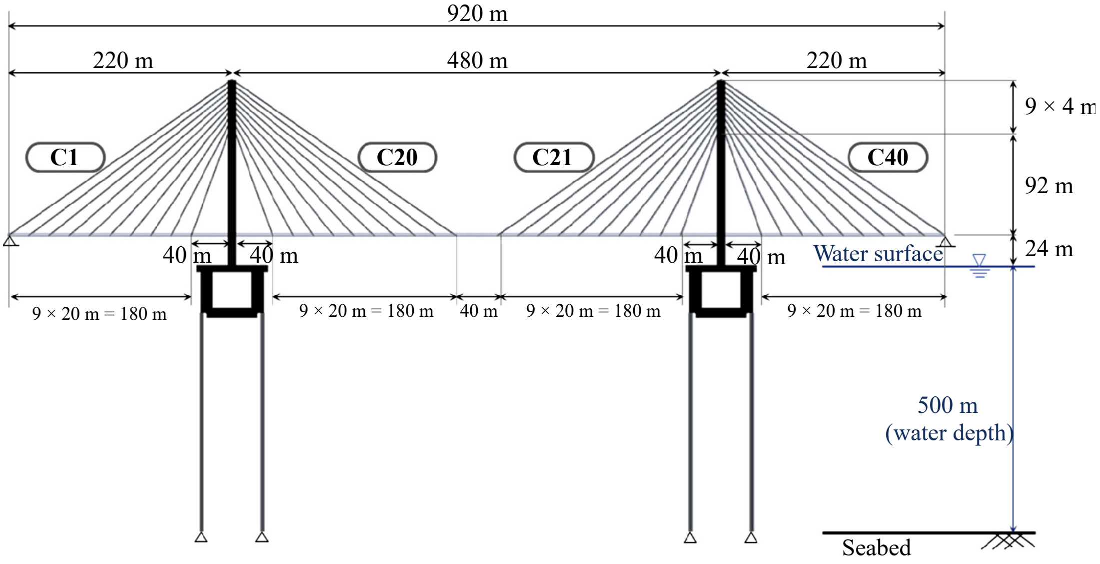
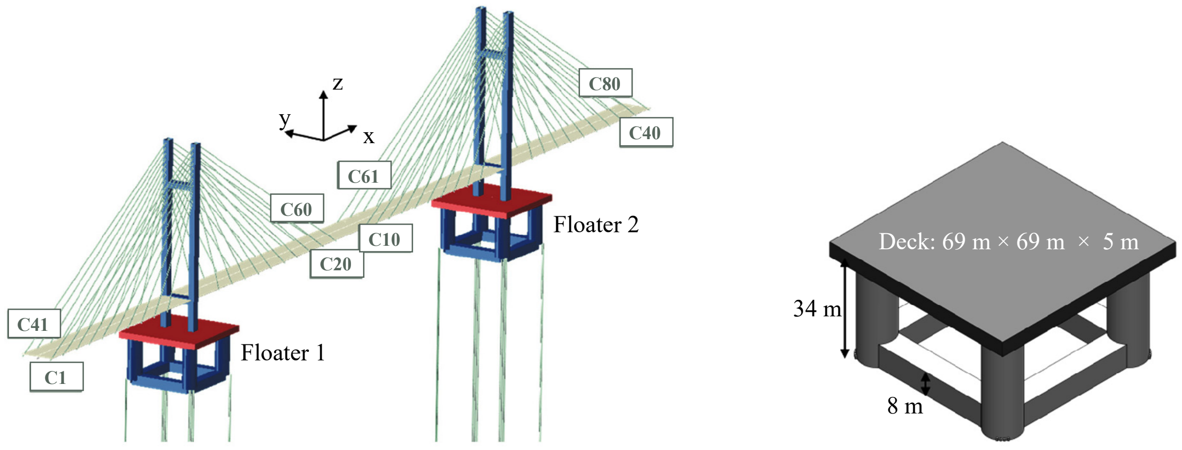


Fig. 2. Analysis model of the floating cable-stayed bridge



(a) Floating cable-stayed bridge

(b) Four column-pontoon type floater

Fig. 3. ABAQUS analysis model

the floating cable bridge was performed considering not only the cable but also the tether.

An initial shape analysis was performed as the 1st analysis step by repeatedly analyzing and updating the initial tension of the tether and cable based on the static dead load of the floating cable-stayed bridge, before performing the hydrodynamic analysis of the wave load. After determining the appropriate initial tension of the tether and cable through the static analysis of the initial shape, a hydrodynamic analysis of the intact condition of the floating cable-stayed bridge was performed as

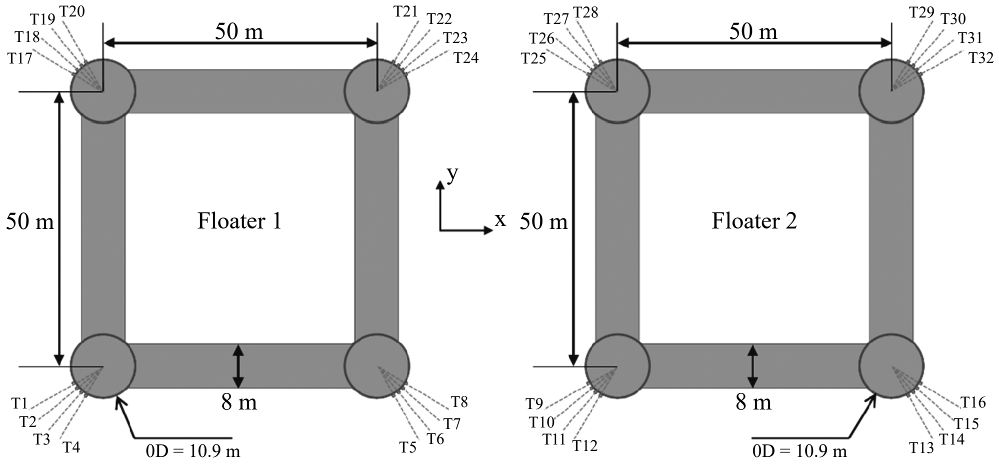
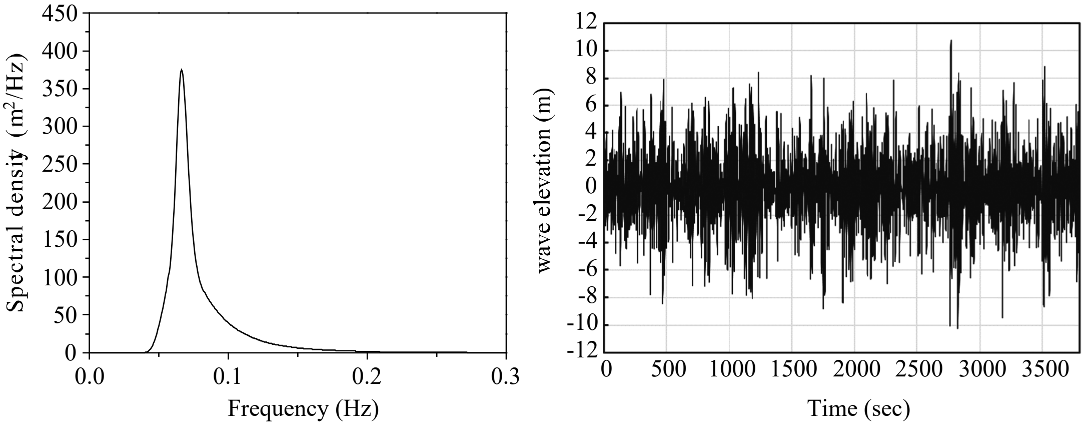


Fig. 4. Position and numbering of tethers attachment



(a) Spectral energy density (b) Time-series wave elevation

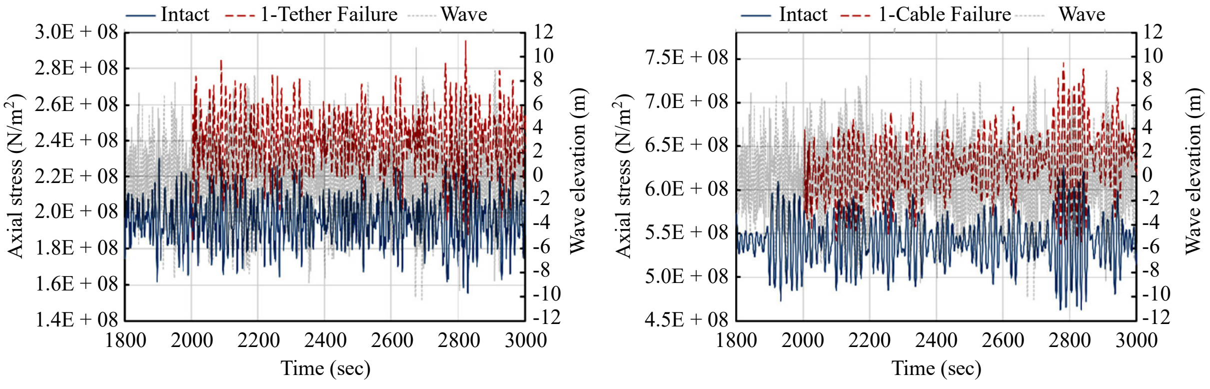
Fig. 5. 100-year return period irregular wave generated by JONSWAP wave spectrum

the 2nd analysis step. To simulate the dynamic behavior of the structure after a sudden fracture, the same hydrodynamicanalysis was performed as the 3rd step after removing the tether or cable element at a specific time of the 2nd analysis step during the continuous wave loading. Further, the sudden failure behavior of the structure was compared and evaluated at the intact condition via FEM analysis. Fig. 1 shows the simulation process of the time-domain sudden failure analysis for the floating cable-stayed bridges.

III. BEHAVIORAL CHARACTERISTICS AFTER SUDDEN FAILURE OF TETHERS AND STAY CABLES UNDER IRREGULAR WAVES

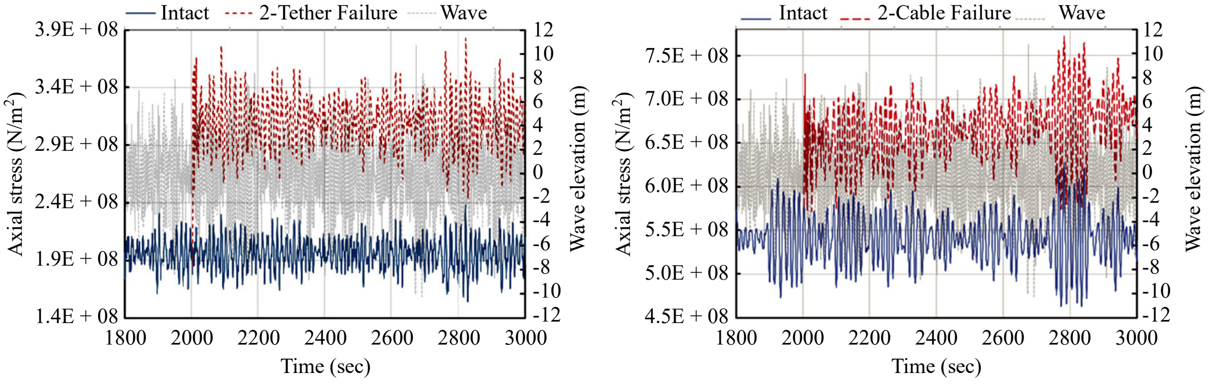
1. Analysis model and environmental condition

As shown in Fig. 2, the analysis model of the floating cable-stayed bridge had a total length, center span, tower height (top of tower to girder), and free water spacing of 920 m, 480 m, 128 m, and 25 m, respectively. The water depth was assumed to be 500 m. As shown in Fig. 3(a), the superstructure is supported by a total of 80 stay cables in a two-sided arrangement, the cables are anchored to H-type floating towers, and the connection between the girder and the floating tower was assumed to be a hinge connection. Fig. 3(b) shows the considered floater type, and Fig. 4 shows the arrangement of the tethers, in which four tethers form one cluster and 16 tethers are mooring each floater. All tethers are API X70 grade steel pipes and their outer diameter and thickness are 0.6 m and 0.02 m, respectively. Table 1 shows the section properties of the main members. For hydrodynamic analysis, the drag coefficient and added mass coefficient of the circular sections of the tethers and columns of the floaters were 1.2 and 1.0, respectively, whereas 2.1 and 1.51 were applied for the rectangular section of the floaters. In this study, the dynamic behavior after the sudden failure of 1, 2 and 4 tethers (in Fig. 4, T1~T4) as well as 1 and 2 cables (in Fig. 3, C20 and C60) were analyzed. Each failure member of the tether and the cable was determined to sequentially disconnect the member receiving the greatest tensile force in each condition.



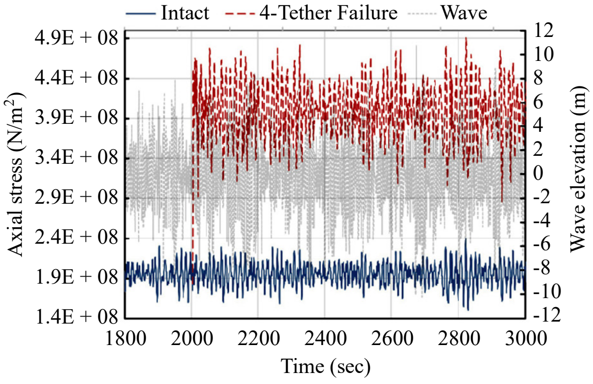
(a) Sudden failure of one tether

(b) Sudden failure of one cable



(c) Sudden failure of two tethers

(d) Sudden failure of two cables



(e) Sudden failure of four tethers

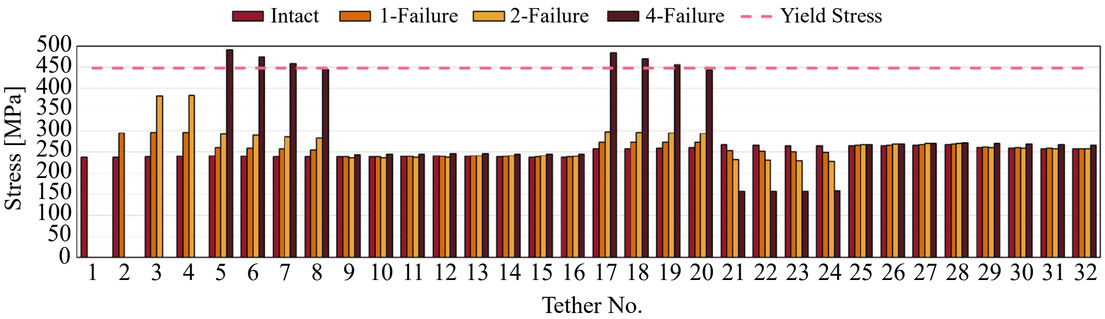
Fig. 6. Nearest axial stress after sudden failure

As shown in Fig. 1**,** in the static analysis step, the dead load of the main members (girder, slab, tower, stay cables, floater, and tethers), buoyancy, and traffic load are applied. After determining the force-equilibrium for the static loading condition, implicit dynamic analysis is conducted for 3,800 s under the irregular wave loading condition in y direction.

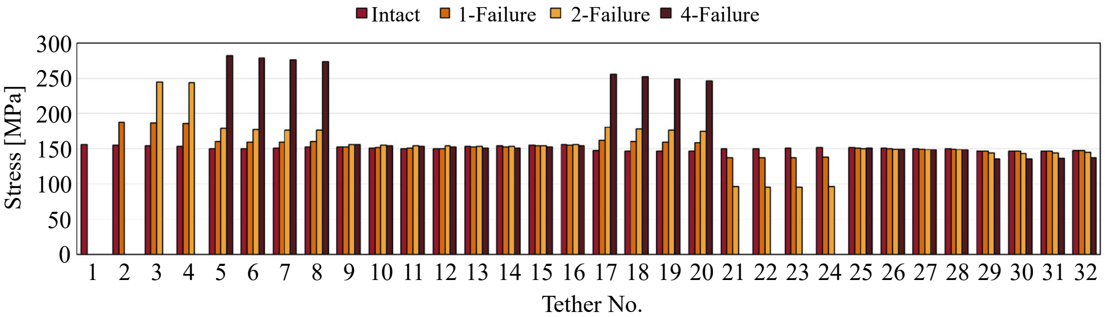
Fig. 5 shows the 100-year return period irregular wave generated through the JONSWAP wave spectrum with a peak period (T_p), a significant wave height (H_s) and an enhancement parameter (γ) of 15.1 s, 11.32 m and 3.3, respectively. The 100-year return period wave condition has been used in a previous study for developing offshore renewable energy facilities in the southern part of Korea (Son et al., 2015).

2. Change of tensile forces of other tethers and stay cables after sudden failure of members

Fig. 6 shows the dynamic tensile force change of the nearest tether or cable after a sudden break in 2,000 s. It can be observed that the transient effect of the tether and cable occurs after 2,000 s when a sudden failure occurs, and the effect is amplified as the number of failure members increases. Fig. 7 and Fig. 8 show the maximum and minimum tension values of the tether and cable after each failure of all members, respectively. In the case of the tether, members 1 to 8 and members

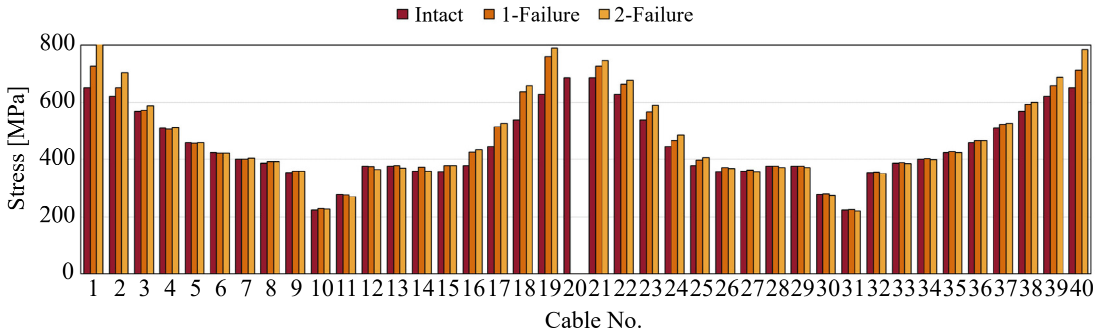


(a) Maximum axial stress

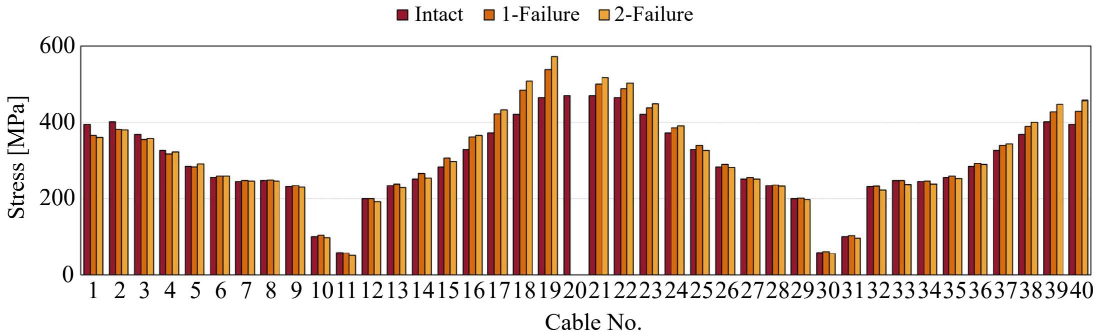


(b) Maximum axial stress

Fig. 7. Axial stresses of tethers after each sudden failure

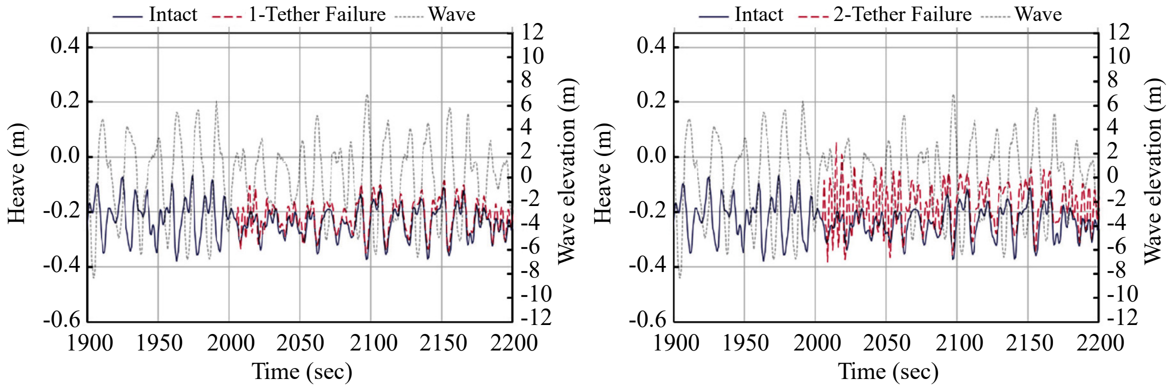


(a) Maximum axial stress



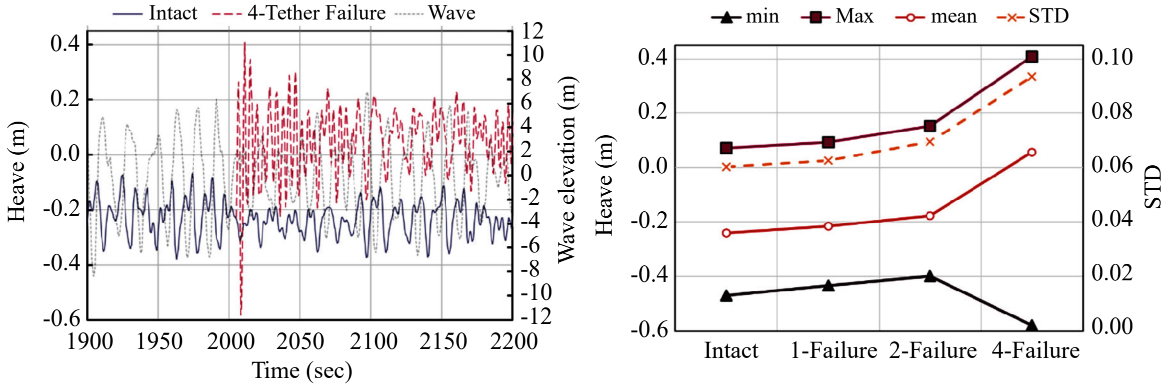
(b) Maximum axial stress

Fig. 8. Axial stresses of cables after each sudden failure



(a) Sudden failure of one tether

(b) Sudden failure of two tethers



(c) Sudden failure of four tethers

(d) Statistical results after sudden failure

Fig. 9. Heave displacement of the girder after tether failure

17 to 24 are mooring floater 1. As evident from Fig. 7, even if the four tethers failure at floater 1, the tensile force change of the tether at floater 2 has a small effect. This means that each floater exhibits partially independent behavior to the superstructure and stayed cable even if the tether is failed. However, when the four tethers suddenly fail, the maximum stress in the adjacent tether exceeds the yield stress, or negative tension occurs. In the case of the sudden failure of the cable, the stress of the cable suddenly fluctuated afterwards. Additionally, there were maximum and minimum stress changes in the tensions of the adjacent cables. However, when analyzing the two cable breaks in this analysis, there was no significant unstable phenomenon.

3. Displacements of the structure after sudden failure of tethers and stay cables

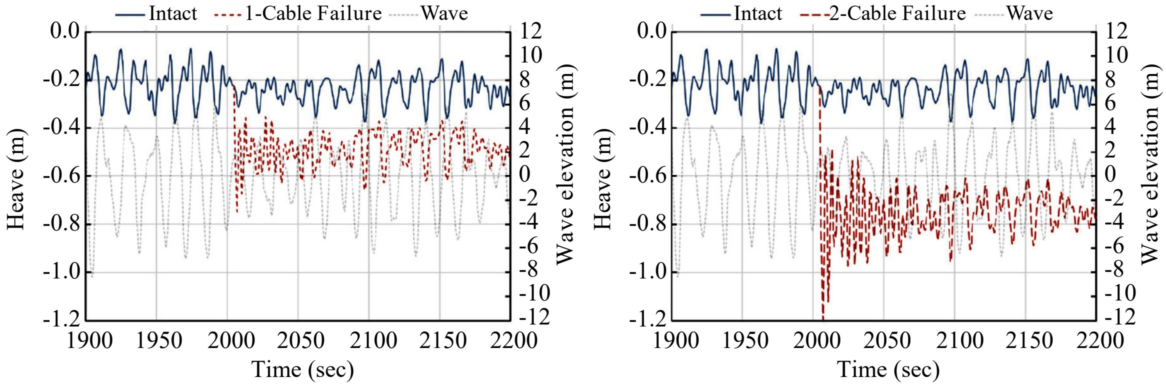
Fig. 9 and Fig. 10 show the heave (vertical displacement) at the center of the girder because of the sudden failure of the tethers and cables, respectively. As shown in Fig. 9, because of the tether's failure, the average heave of the girder increases owing to the loss of the force that holds the buoyancy of the floater; however, the standard deviation increases, and a dynamic amplification effect is caused by the sudden failure. The effect of the sudden failure of a tether is relatively small compared to the stress of the tether. Because negative tension occurred in the stress results when the four tethers failed, the heave change of the girder also caused a larger displacement in the downward direction.

In contrast, in the case of cable failure, it can be observed that the cable supporting the girder in the upward direction is failed, and the heave displacement of the girder decreases. From Fig. 10, it can be confirmed that the sudden failure of the cable, which directly supports the girder significantly affects the displacement of the girder.

IV. CONCLUSIONS

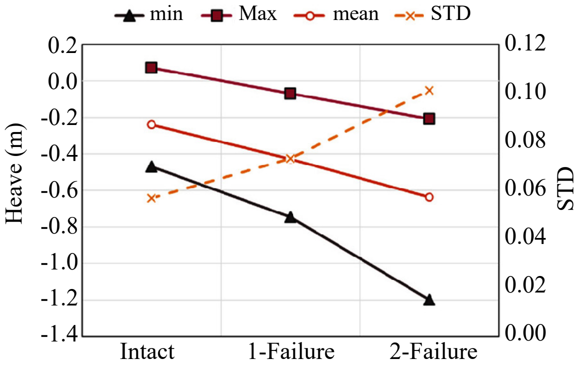
In this study, an analytical procedure was proposed to evaluate the dynamic behavior of floating cable-stayed bridges after the sudden failure of the tether and cable. The behavior of the time domain after sudden failure was evaluated based on this. An irregular wave load of a 100-year return period was applied, and the stress change and heave displacement of the girder were evaluated according to the number of sudden failure members. The conclusions of the study are as follows:

A In an arrangement where four tethers form one cluster and four clusters hold one floater, significant displacement occurred when all the tethers of the cluster failed, and the stresses of the remaining tethers near the failed



(a) Sudden failure of one cable

(b) Sudden failure of two cables



(c) Statistical results after sudden failure

Fig. 10. Heave displacement of girder after cable failure

tethers were amplified. Therefore, to secure stability against tether replacement or failure, a cluster of tethers moored to a floater must be composed of three to four, or more tethers.

B The analysis results indicated that there was no significant instability when two tethers in one cluster were failed. However, in the case of a sudden failure, it takes considerable time to repair after the failure, unlike the replacement of the tether. The behavior after this causes stress amplification to adjacent tethers until repairs are completed. Therefore, it is necessary to further evaluate the fatigue caused by the stress range amplified by the sudden failure of the tether.

C Although all the main structural members are connected, tether failure in one floating tower does not significantly affect the structural response change of the other tower. However, a more intensive study should be conducted to evaluate and verify these behavioral characteristics considering more parameters such as the tower-girder stiffness ratio, center-and side-span length ratio, and arrangement of the stay cables and tethers.

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