Homogeneous Wave Load Effects on the Connections of Main Parts of Side-Anchored Straight Floating Bridge

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In this paper, a numerical study is presented to investigate wave force on the connections of main parts of a side-anchored straight floating bridge concept for the Bjørnafjorden fjord crossing. The floating bridge is supported by 18 pontoons, and three groups of mooring lines are employed to restrain the bridge against horizontal loads and increase its transverse stiffness. The created wave forces at the connections of pontoon-column and column-girder of the floating bridge considering the effects of short-crested and long-crested waves, varying wave direction, hydrodynamic interaction between pontoons, and mooring system are analyzed. It is found that short-crested and long-crested waves depending on their direction decrease or increase the wave forces on the joints. Considering that the effect of hydrodynamic interaction between pontoons can increase or reduce the wave forces and moments created in the joints, which means the neglect of the hydrodynamic interaction effects between the pontoons to simplify the modeling of this type of floating bridge, may be unacceptable. Moreover, the results showed that the bridge mooring system does not merely reduce the wave forces and moments at joints along the bridge.

1. Introduction

Floating bridges are structures that create a span over a body of water that is between two lands using a set of pontoons and a continuous girder. Ordinarily, this type of bridge is suggested in areas where the construction of a fixed bridge is not cost-effective due to deep water, or it is not possible to build a foundation with necessary resistance due to the loose and soft seabed. On the coastline of Norway, there are many deep and wide fjords between which ferries provide access. This has increased the time and cost of transportation. Some of these fjords have a considerable depth of about 1300 m and a width of about 6000 m. The Norwegian Public Road Administration (NPRA) is examining floating bridge concepts to connect the fjords on the coastal road between Trondheim and Kristiansand.

The Bjørnafjorden fjord, due to its 550 m depth and 5 km width, has received the most attention (Figure 1(a)). Hitherto, several floating bridge concepts such as a floating bridge with mooring, floating bridge without mooring, suspension bridge on floating foundations, suspension bridge on fixed foundations, and submerged floating tunnel have been suggested and investigated by working groups to cross this fjord. The suspension bridge on fixed foundations and the submerged floating tunnel were excluded due to high cost and tough construction conditions, and the other three concepts were examined more [1]. As shown in Figure 1(b), the side-anchored straight bridge (SASB) is a straight bridge, including a long steel girder, which is placed on the 18 moored pontoons. In this concept, the mooring line system resists against the transverse and longitudinal loads, and buoyancy resists against vertical loads [2]. The curved end-anchored bridge (CEAB) is an inclined arch bridge girder resting on 19 unmoored pontoons, where the curve provides persistence against the loads by using the axial force from the end anchoring (Figure 1(c)). The CEAB and SASB concepts have a navigation channel; depending on their location, the configuration of the bridge may be changed [3]. The suspension bridge with floating pylons consists of a three-span bridge with two floating tension leg
Among these, SASB and CEAB concepts for crossing Bjørnafjorden fjord have been further researched. Fredriksen et al. [5] performed a hydrodynamic model of SASB to analyze the global bridge response. They tried to reduce the wave forces on the floating bridge girder by changing the pontoon geometry and adding a bottom flange. Cheng et al. [6–8] investigated the CEAB concept under different conditions for crossing Bjørnafjorden fjord. First, they analyzed the effect of varying water depth at the ends of the bridge, the viscous drag force on pontoons, and short-crestedness and second-order wave loads on the forces and moments of the bridge girder under the homogeneous wave. In the other work, they compared homogeneous and inhomogeneous waves' effect on dynamic responses of CEAB. Then, they investigated the CEAB under the wind, wave, and current loads comprehensively. Dai et al. [9] studied a numerical model of the hydroelastic response of a SASB by considering the various effects of inhomogeneous wave loads consisting of the wave direction, wave height, and peak period. Viuff et al. [10] presented a numerical study of the effects of wave directionality on the extreme response for a CEAB and investigated both vertical and transverse displacement response spectra and extreme Von Mises stress in the bridge girder cross-section. In the mentioned studies, the effect of hydrodynamic interaction between pontoons was neglected. Xiang et al. [11] performed a CEAB model with 46 pontoons and investigated the effect of hydrodynamic interaction between floating bridge pontoons on the global responses of the bridge. They showed that the hydrodynamic interaction makes the hydrodynamic coefficients (added mass, potential damping, diffraction force, and response amplitude operator) extremely resonant, and the bridge weak/strong axis bending moments may reduce or increase in the same wave conditions.

The CEAB concept can resist transverse loads without requiring the mooring line system; however, due to a wide span of about 5 km, the bridge stiffness in its curvature plane may be reduced. Also, a curved bridge without mooring systems lacks hydrodynamic damping which can affect the dynamic responses of the bridge. The SASB concept seems a simple and cost-effective solution, which does not rely on structural members to withstand transverse loads. This is controlled by a mooring system, which increases the transverse stiffness of the bridge and adds its viscous hydrodynamic damping [9]. The CEAB and SASB concepts have many structural differences that can have different responses under the same environmental conditions. Choosing an option between these concepts requires much consideration that is not within the scope of this study. However, in this study, the SASB concept is considered to be investigated. All the studies reviewed in the previous paragraph were performed to investigate the wave force in different conditions on the bridge girder or pontoons. Predicting the wave force at the connection of the main parts of the bridge, such as the connections of the pontoons to the columns (PC) and the columns to the girder (CG), allows for a more detailed look at this problem, which has not been reported in the open literature. In addition, it can be a starting point for the studies of fatigue damage of joints,
which is an essential point in the bridge design. Therefore, in this paper, a numerical model of the SASB under homogeneous wave load is presented to investigate the effects of wave direction, short-crested wave, hydrodynamic interaction between pontoons, and mooring system on the created wave force at pontoon-column and column-girder connections along the SASB.

2. Description of SASB Concept in a Fjord

In this study, the SASB concept for crossing Bjørnafjorden is chosen for investigation. This concept is proposed by COWI [12]. As shown in Figure 2(a), this bridge has 445 m length with two main parts, high and floating bridge. The floating bridge consists of a steel girder placed on 18 floating pontoons with a constant distance of 203 m and has a low part, which is increasing at the connection to the high part from 18 m to 51 m. In the south end, there is a cable-stayed bridge with a main span of 450 m and a back span of 310 m, to which the girder in the high part of the floating bridge is connected. This is designed for the required navigation channel. The cable-stayed system of the high bridge is supported by an A-shape tower with a height of 215 m. The bridge girder is fixed on a caisson structure (48 m × 28 m × 50.5 m) in the northern and southern abutment. As shown in Figure 2(b), in this concept, there are three pontoons in axes A5, A11, and A17 that are moored to the seabed with eighteen mooring lines. See reference [12] for more details.

2.1. Wave Conditions in the Fjord. The SASB concept is subjected to environmental loads such as waves, wind, and current. In this study, only wave condition is considered, and wind and current conditions are neglected. The Bjørnafjorden fjord, due to its complex topology, has different environmental conditions than the open sea. Typically, two types of waves, such as swell (from the ocean) and wind waves (created by local winds), are generated in a fjord. According to Cheng et al. [13], as a field investigation, three Datawell Wave Riders (DWRs) were deployed to control the wave conditions, and the results showed that the wave field across the Bjørnafjorden is inhomogeneous. It was also indicated that most waves are short-crested and created by wind. Lothe and Musch [14], as a numerical simulation, showed that the swell is approximately small, and wind waves are greatly larger. An inhomogeneous wave has variable parameters such as random phase angle, significant wave height, peak period, and principal wave direction, and these parameters are different around each pontoon along the SASB. In this study, the wave field is considered homogeneous, which means all the parameters mentioned are identical for all pontoons. Since this study focuses on wave load effects on connections of SASB main parts, this simplification seems logical. It has been specified that the JONSWAP spectrum corresponds well with the waves formed in the Bjørnafjorden fjord [15]. The classic form of the JONSWAP spectrum using fetch and wind speed was undertaken by Houmb and Overvik [16]. The spectral ordinate at a frequency is provided by

\[
S(\omega) = \frac{\alpha g^2}{\omega^4} \exp\left(\frac{5\omega^4}{4\omega_p^4}\right),
\]

(1)

where \(\omega_p\) is the peak frequency in rad/s, \(\gamma\) is the peak enhancement factor, and \(\alpha\) is a constant that relates to the wind speed and the peak frequency of wave spectrum, and

\[
\alpha = \exp\left[\frac{(\omega - \omega_p)^4}{2\sigma^2\omega_p^4}\right],
\]

(2)

\[
\sigma = \begin{cases} 
0.07, & \text{where } \omega \leq \omega_p, \\
0.09, & \text{where } \omega > \omega_p.
\end{cases}
\]

Because \(\alpha\) is a constant, the integration of this spectrum can be expressed as

\[
m_0 = \int_0^\infty S(\omega)d\omega = \alpha \int_0^\infty \frac{\gamma^2}{\omega^4} \exp\left(\frac{-5\omega^4}{4\omega_p^4}\right)d\omega = \left(\frac{H_s}{4}\right)^2.
\]

(3)

Thus, if \(\gamma, \omega_p,\) and \(H_s\) are known, then the variable \(\alpha\) can be defined as

\[
\alpha = \frac{(H_s/4)^2}{\int_0^\infty \left(\gamma^2/\omega^4\right) \exp(-5\omega_p^4/4\omega^4)d\omega}
\]

(4)

For short-crested wave, the directional spreading follows the cos-\(n\) distribution, and thus, the direction distribution function \(D_\theta(\theta)\) is defined by

\[
D_\theta(\theta) = \frac{\Gamma(1 + (n/2))}{\sqrt{\pi}\Gamma((1/2) + (n/2))} \cos^n(\theta - \theta_p),
\]

(5)

where \(n\) is the spreading coefficient and \(\theta_p\) is the principal (main) wave direction.

The wave conditions are based on the metocean design basis for Bjørnafjorden with a return period of 100 years, which is shown in Table 1 [17].

3. Numerical Model of SASB

As shown in Figure 3, a three-dimensional numerical model of SASB is performed using ANSYS AQWA, which is a potential-flow-based boundary element method (BEM) code. This solver performs the mooring system analysis by the finite element method (FEM). This method is well verified in modeling a structure similar to a floating bridge [18]. Due to the long length of the bridge and software limitations, it was decided to perform modeling with a scale of 1 : 10. Modeling was scaled using Froude similarity. This study focuses on the floating part of the bridge. Therefore, modeling has been done only for the floating bridge part, and the high bridge part is neglected. Figures 3(a) and 3(b) show plan and elevation views of the model. As shown in Figure 3(c), the pontoons are idealized as six-degrees-of-
freedom (6-DOF) rigid bodies with specific stiffness, damping, and mass matrices. The deck and columns are modeled as rigid bodies connected by rigid connections to each other. The mooring system is modeled as nonlinear bar elements. Since Cheng et al. [6] showed that water depth variations do not have a significant effect on wave loads, in this study, water depth is considered constant during all calculations. The simplifications mentioned may not have much impact on the results because this study does not intend to obtain the exact amount of load on the bridge for design; instead, it plans to compare the effect of some influential parameters in different conditions of the SASB problem. However, the results of modeling will be compared in the next section with COWI Project. Figure 3(d) shows the bridge connections details around pontoons 13 and 14. It can be realized that the bridge deck is connected to the columns by a rigid joint, which is defined as \( JC_{1}D_{1} - JC_{18}D_{18} \). The columns are shown with symbols C1–C18, which are rigidly connected to pontoons by \( JP_{1}C_{1} - JP_{18}C_{18} \). The pontoons are shown as P1–P18. The decks are separated in the middle of each span and are shown with symbols D1–D18, and they are connected with rigid joints \( JD_{1}D_{2} - JD_{17}D_{18} \). The deck is segregated from the high bridge at a distance of 45 meters from pontoon 1 in the south and fixed as the north’s support. The cross-section of the deck is constant along the floating bridge and has a height of 0.65 meters. The length of columns is 4.33 m to 0.86 m for axis A3-A8 and is 0.75 m for axis A9-A20. The diameter of columns is 1 m. Details of the pontoons and mooring system are shown in Tables 2 and 3, respectively. More details are reported by COWI [12].

3.1. Wave Load Modeling. The numerical source distribution method for calculating the first-order and second-order wave excitation forces is defined. Three-dimensional panel methods are the most common numerical methods to investigate the hydrodynamic performance of a large-volume structure in waves. These methods are based on the fluid potential theory and describe the structure surface by a set of

| Sectors (°) | \( H_{s} \) (m) | \( T_{p} \) (s) |
|------------|----------------|---------------|
| 345–75     | 1.5            | 5             |
| 75–105     | 2.8            | 6.6           |
| 105–165    | 1.6            | 5.3           |
| 165–225    | 1.9            | 5.3           |
| 225–315    | 2.4            | 5.9           |
| 315–345    | 2.5            | 6.2           |
diffraction panels. Here, the linear approach is employed to show the short-crested waves (multidirectional sea waves) as the summation of a large number of wave components; for example,

\[ \zeta(X, Y, t) = \sum_{m=1}^{N_d} \sum_{j=1}^{N_m} a_{jm} e^{(k_{jm} X \cos \chi_m + k_{jm} Y \sin \chi_m - \omega_{jm} t + \alpha_{jm})}, \]

where \( N_d \) and \( N_m \) are the number of wave directions and number of wave components along each wave direction \( \chi_m (m = 1, N_d) \), \( a_{jm} \) is the wave amplitude, \( \omega_{jm} \) is the wave frequency, and \( k_{jm} \) is the wave number, and \( \alpha_{jm} \) is the random phase angle of a wave component \( jm (j = 1, N_m) \). When the multidirectional wave elevation is generally represented by (5), the sum of the Froude-Krylov and diffracting forces and moments as the first-order wave excitation force and moment can be defined.

**Figure 3:** Sketch of SASB model details: (a) plan view, (b) elevation view (dimensions in m), (c) 3D view, and (d) connections details around pontoons 13 and 14.
\[ F^{(1)}(t) = \sum_{m=1}^{N_s} \sum_{j=1}^{N_n} a_{jm} E(t) \left[ F_i(\omega_{jm}, \beta_m) + F_d(\omega_{jm}, \beta_m) \right] \epsilon_{jm} e^{i(k_{jm} x_g \cos \chi_m + k_{jm} y_g \sin \chi_m - \omega_{jm} t + \alpha_{jm})}, \]

where \( E(t) \) is the Euler rotation matrix at a time \( t \), \( \beta_m = \chi_m - \theta_3(t) \) is the relative heading angle of the \( m \)-th sub-directional wave (relative to the structure, where \( \theta_3(t) \) is the instantaneous yaw angle of the structure), and \( F_i + F_d \) is the total first-order wave excitation force induced by a unit amplitude incident wave with frequency \( \omega_{jm} \) and wave direction \( \beta_m \).

\[ F^{(2)}(t) = \sum_{m=1}^{N_s} \sum_{j=1}^{N_n} \sum_{k=1}^{N_k} a_{jm} a_{kn} E \left[ P_{jk}(\beta_m, \beta_n) \epsilon_{jm} \epsilon_{kn} \epsilon_{jm} e^{i(k_{jm} x_g \cos \chi_m + k_{jm} y_g \sin \chi_m - \omega_{jm} t + \alpha_{jm})} \right] \]

where \( \epsilon_{jm} = k_{jm} X_g \cos \chi_m + k_{jm} Y_g \sin \chi_m + \alpha_{jm} \) and \( \epsilon_{kn} = k_{kn} X_g \cos \chi_m + k_{kn} Y_g \sin \chi_m + \alpha_{kn} \).

### 3.2. Validation of the Numerical Model.

The purpose of this section is to compare the numerical results of the SASB model with the COWI project. Since the purpose of this study is to investigate the wave forces on the connections of the columns to the girder and the pontoons to the columns, in the numerical model, to verify the prediction of these forces, the girder is divided into several parts at each axis of the floating bridge, and the girder parts are connected by a rigid joint to each other. Figure 4(a) shows the connections of axes 13 and 14 as examples. Then the moments in these joints are compared with the moments on its peer axis in the COWI project. In order to determine the effect of the mesh and the time step on the results, four different meshes with a maximum element size of 1, 0.8, 0.7, and 0.6 m with a time step of 0.5 s were selected. Then, they are calculated for the time history of the bending moment about the \( Y \)-axis of the girder on axis 9 of the bridge (\( M_{Y} \)). As shown in Figure 5(a), the result has very little variation in the 0.6 and 0.7 m meshes. Therefore, the 0.7 m mesh was selected to compare the time steps of 1, 0.5, 0.3, and 0.2 s. As shown in Figure 5(b), the result has low variation in the time steps of 0.2 and 0.3 s. Finally, a mesh size of 0.7 m with a time step of
0.3 s was selected as the optimal mesh and time step for the simulations of this study. Figures 6 and 7 show a comparison between the results of the COWI project and the numerical model in the maximum bending moments created on girder axes (Y and Z) during one 4000 s simulation. Two waves with directions 270° and 225°, height ($H_s$) 0.3 m, and period ($T_p$) 1.89 s were chosen for investigation. The results show that the numerical model predicts about 7.5% larger moments on average for all axes, and the trend of increasing and decreasing the moments in the numerical model and COWI project has been almost the same in all axes. Therefore, it can be concluded that the numerical model is reliable in predicting wave forces on floating bridge connections.

4. Results and Discussion

In this section, a series of load cases (LCs), as shown in Table 4, were considered to investigate the effects of incident wave direction, short-crested waves, hydrodynamic interaction between pontoons, and the mooring of pontoons on wave forces created in the connections of SASB. Since waves come primarily from the west and northwest of the fjord to the bridge site [13], two directions of 270° (LC1, LC2, LC3, and LC4) and 315° (LC5, LC6, LC7, and LC8) were considered for the incident wave. LC1, LC3, LC5, and LC7 are defined for column-girder joints, and LC2, LC4, LC6, and LC8 are defined for pontoon-column joints. The wind waves created in a fjord may be in the short-crested form. Therefore, the effect of changing the waves from long-crested to short-crested on the wave forces hitting the SASB must be investigated. Long-crested waves are described as waves generated from one direction. In contrast, a short-crested wave is described as the linear sum of several long-crested waves spread to different angles, where the direction and magnitude created are randomly diverse. The short-crested waves are with a small directional distribution exponent $n = 4$ (spreading). LC1, LC2, LC5, and LC6 are utilized to determine the effect of long-crested waves, and LC13, LC4, LC7, and LC8 are defined for the impact of the short-crested waves. For all LC1 to LC8, calculations are performed in two modes with and without considering hydrodynamic interaction between the pontoons. Moreover, LC1 and LC5 (long-crested wave with directions 270° and 315°) are presented with two modes, moored and unmoored, to investigate the effect of mooring lines on the axial forces and bending moments at joints along the bridge.
The results of created forces and moments at the joints under different LCs for specific axes of the SASB (A3, A5, A10, A11, A12, A17, and A20) are presented. These axes were selected from the whole SASB axes with a uniform distribution considering the first, the end, and the location of moored pontoons. Furthermore, these axes are included locations of the SASB with low-frequency resonant eigen-modes, which are excited because of second-order difference-frequency wave loads. Figures 7–12 present the statistical results of axial forces ($F_x$, $F_y$, and $F_z$) and bending moments ($M_x$, $M_y$, and $M_z$) on joints (JPC and JCG) along the bridge under different LCs during 4000 s simulation. These results include the maximum, mean, and standard deviation (SD) of values. In general, it can be concluded by comparing the standard deviation in axial wave forces that $F_z$ has the least values than $F_x$ and $F_y$ for all LCs. The hydrodynamic interaction between the pontoons had a more significant effect on $F_x$ than $F_z$ and $F_y$.

As shown in Figure 8, from the results of standard deviation in $F_x$, the following can be realized: (1) becoming the wave direction from 270° to 315° has raised $F_x$ on the joints up to about 20 times for long-crested wave and up to 3 times for short-crested wave; (2) changing long-crested wave to short-crested wave has increased $F_x$ on the joints up to about 25 times for the wave with direction 270° and also it has decreased down to about 3.5 times for the wave with direction 315°; (3) in JPC and JCG, almost equal $F_x$ is created, except in the load case of the long-crested wave with direction 270° where $F_x$ is created in JCG about 65% more than JPC; (4) $F_x$ has increased significantly in the short-crested and long-crested waves with direction 270° by considering the hydrodynamic interaction between pontoons.
in force has had a more significant impact on the axes close to the abutment than the axes close to the middle of the bridge. However, for the wave with direction 315°, the hydrodynamic interaction between pontoons increases $F_x$ on joints in the long-crested and decreases $F_x$ in the short-crested.

**Figure 8:** Statistical values of axial force on joints in the X-direction: (a) maximum, (b) mean, and (c) SD.

**Figure 9:** Statistical values of axial force on joints in the Y-direction: (a) maximum, (b) mean, and (c) SD.
Figure 9 shows the statistical results regarding axial force $F_z$. The standard deviations in $F_z$ are approximately similar for LC5-LC8. It means changing long-crested wave to short-crested wave in the direction 315° has not affected $F_z$. However, for direction 270°, $F_z$ has decreased about 25% by changing long-crested wave to short-crested wave. $F_z$ on $I_{CG}$ and $I_{PC}$ is nearly similar for all axes under all LCs. The hydrodynamic interaction between pontoons has not had a considerable effect on $F_z$ for all axes and LCs.

As shown in Figure 10, from the results of maximum $F_z$, the following can be obtained: (1) variations of the wave direction and changing long-crested wave to short-crested wave have not affected $F_z$; (2) the hydrodynamic interaction between pontoons has not had a significant impact on $F_z$ for all of the axes and LCs; (3) in the axes A5, A11, and A17 that the pontoons are moored, a notable reduction has been observed in $F_z$ about 66%; (4) in the axis of A1, $F_z$ on $I_{CG}$ has been more about 30% than $I_{PC}$. Nevertheless, the standard deviations in $F_z$ have given different results. In this case, $F_z$ has not changed notably under any of the axes and LCs.

Figures 11–13 show the statistical values of bending moment ($M_x$, $M_y$, and $M_z$) due to wave forces on the connections $I_{PC}$ and $I_{CG}$ along the bridge. The results indicate the hydrodynamic interaction between the pontoons has more effect on $M_y$ and $M_z$ than $M_x$. The moments of $M_x$, $M_y$, and $M_z$ can have different values depending on the type of LC. For example, LC1 creates a larger magnitude of $M_x$, LC5 creates a larger magnitude of $M_z$, and LC7 creates a more significant magnitude of $M_y$. The results of $M_x$ show that (1) changing the wave direction from 270° to 315° decreases $M_x$ on the joints down to about 31% for long-crested wave and down to about 9% for short-crested wave; (2) changing long-crested wave to short-crested wave decreases $M_y$ on the joints down to about 10% for the wave with direction 270° and down to about 7% for the wave with direction 315°; (3) $M_y$ on $I_{CG}$ has been about 35% more than $I_{PC}$; and (4) the hydrodynamic interaction between pontoons has not had a substantial effect on $M_z$ for all of the axes and LCs.

From the results of $M_y$, the following can be realized: (1) changing the wave direction from 270° to 315° has increased $M_y$ on $I_{CG}$ and $I_{PC}$ up to about 92% and 35%, respectively, for short-crested wave. Furthermore, this change of direction has increased $M_y$ on $I_{CG}$ and $I_{PC}$ up to 17 times and 40 times, respectively, for long-crested wave. (2) Changing long-crested wave to short-crested wave increases $M_y$ on $I_{CG}$ up to about 20 times and on $I_{PC}$ up to 40 times for the wave with direction 270° and also increases $M_y$ on $I_{CG}$ up to about 69% and on $I_{PC}$ up to about 27% for the wave with direction 315°. (3) $M_y$ on $I_{CG}$ has been about 83% for LC1 and LC2, 59% for LC3 and LC4, 58% for LC5 and LC6, 22% for LC7 and LC8 more than $I_{PC}$ in all axes. (4) The hydrodynamic interaction between pontoons has increased $M_y$ on joints under LC1, LC2, LC3, LC4, LC5, and LC6. Also, it has decreased $M_y$ under LC7 and LC8.

The results of $M_z$ indicate the following. (1) Changing the wave direction from 270° to 315° has raised $M_z$ on joints up to about 100 times for long-crested wave and up to 20% for short-crested wave. (2) The change from long-crested wave to short-crested wave increases $M_z$ on joints up to about 53 times for the wave with direction 270° and decreases it down to about 52% for the wave with direction 315°. (3) $I_{PC}$ and $I_{CG}$ almost identical $M_z$ is created, and variations are not notable in all axes. (4) The hydrodynamic interaction...
between pontoons decreases $M_z$ on joints under LC3, LC4, LC5, LC6, LC7, and LC8 and increases it under LC1 and LC2.

Short-crested and long-crested waves can reduce or increase the forces and moments on the joints depending on their direction. The hydrodynamic interaction between the
Figure 13: Statistical values of bending moment on joints in the Z-direction: (a) maximum, (b) mean, and (c) SD.

Figure 14: The standard deviation of axial forces and bending moments on joints along the bridge in LC1 with two modes moored and unmoored: (a) $F_x$, (b) $F_y$, (c) $F_z$, (d) $M_x$, (e) $M_y$, and (f) $M_z$. 
pontoons, depending on the wave direction and long-crested wave or short-crested wave, causes an increase or decrease in $F_x$, $M_y$, and $M_z$ and did not have much effect on $F_y$, $M_x$, and $M_z$. By turning the short-crested wave to a long-crested wave and variation of the wave direction, at JPC and JCG, approximately $F_x$, $F_y$, $F_z$, and $M_z$ are created similarly. In contrast, values $M_y$ and $M_x$ are significantly higher at JCG.

The impact of mooring lines on the axial forces and bending moments at joints along the bridge in LC1 and LC5 is also studied. Figures 14 and 15 show the standard deviation of axial forces and bending moments on joints along the bridge in two states of moored and unmoored bridge under the long-crested wave with directions 270° and 315°. As shown in Figure 14, moored bridge under the long-crested wave with direction 270° (LC1) has had more amount of $F_x$, $M_y$, and $M_z$ than $F_y$, $F_z$, and $M_x$. As shown in Figure 15, moored bridge under the long-crested wave with direction 315° (LC5) has had more amount of $F_x$, $F_y$, $M_x$, and $M_z$ than $F_y$, $F_z$, and $M_x$. These variations of forces and moments have not been the same along the bridge. In LC1, $F_x$, $M_y$, and $M_z$ at the side axes have been more than the central axes of the bridge. However, the contrast of this aspect has occurred in LC5. In LC1, $F_z$ is created in moored axes of the bridge (A5, A11, and A17) more than other axes. In the unmoored axes, $F_z$ was the same for the moored and unmoored bridge. What is clear from these results is that the amount of force and moment along the moored bridge was more stable than the unmoored bridge.

5. Conclusion

In this paper, a numerical study is performed to predict wave force on the connections of main parts of a side-anchored straight floating bridge. The considered floating bridge model is based on a conceptual design for crossing the Bjørnafjorden fjord. Modeling is performed using a potential-flow-based boundary element method code. The floating bridge model is idealized. Comparing the results of the idealized bridge model with an independent study revealed that the idealized bridge model is reliable in predicting wave forces. This study comprehensively discussed several effects of hydrodynamic loads, containing short-crested and long-crested waves, varying wave direction, hydrodynamic interaction between pontoons, and mooring system on created wave forces at pontoon-column and
column-girder joints of the floating bridge. The following conclusions are summarized on the results presented in this study:

(i) Short-crested and long-crested waves can reduce or increase the wave forces and moments on the pontoon-column \((I_{PC})\) and column-girder \((I_{CG})\) joints of the floating bridge depending on incident wave direction.

(ii) The hydrodynamic interaction between the pontoons, depending on the wave direction and long-crested wave or short-crested wave, causes an increase or decrease in the axial wave force on the joints in the longitudinal axis of the bridge \((F_{x})\), bending moment in the direction perpendicular to the longitudinal axis of the bridge \((M_{y})\) and bending moment in vertical direction \((M_{z})\), whereas it did not have a substantial effect on axial wave force on the joints in the vertical direction \((F_{z})\), axial wave force in the direction perpendicular to the longitudinal axis of the bridge \((F_{y})\), and bending moment of the longitudinal axis of the bridge \((M_{x})\).

(iii) By altering the short-crested wave to a long-crested wave and variation of the wave direction, at \(I_{PC}\) and \(I_{CG}\), approximately \(F_{x}, F_{y}, F_{z}\), and \(M_{x}\) are created similarly, while, at the same time, the values of \(M_{y}\) and \(M_{z}\) are significantly higher at \(I_{CG}\).

(iv) The axial wave forces and moments on the pontoon-column and column-girder joints of the moored and unmoored bridge have changed with the variation of wave direction. The results showed that the bridge mooring system does not merely reduce the wave forces and moments at joints along the bridge.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Authors’ Contributions**

All authors contributed equally to this work. Meysam Rajabi carried out conceptualization, methodology, investigation, data curation, writing of original draft, formal analysis, visualization, and validation. Hassan Ghassemi provided supervision and writing (review and editing). Hamidreza Ghafari contributed to writing (review and editing).

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