Research and Development in Connector Systems for Very Large Floating Structures

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ABSTRACT

In recent years, Very Large Floating Structures (VLFS) technology has attracted much attention for its sustainable and eco-friendly approach in creating land from the sea. Owing to the massive size, VLFS are usually fabricated as a number of floating modules in shipyards, towed to site and connected on sea. To ensure the functionality of such connected VLFS, effective connector systems are essential. The connector system must address issues related to the relative motion between adjacent modules and be able to sustain forces as a result of wave motion. This paper presents a critical review on the research and development in connector systems for modularized VLFS. Various design concepts for connector systems are first categorized and their working principles outlined. Research studies on hydroelastic analysis of VLFS and the effectiveness of connector systems in reducing the hydroelastic responses and internal stress resultants in connectors are also reviewed. In addition, potential technical challenges on the determination of connector stiffness in practical designs are discussed. Finally, some recommendations and suggestions for future practice are provided.

Keywords: Connector Systems; Hydroelastic Responses; Internal Stress Resultants; Very Large Floating Structures.

1. INTRODUCTION

Very large floating structures (VLFS) have been touted to be a better alternative approach in creating land space on the sea than the traditional land reclamation technique. Their advantages include the freedom in site selection, low construction cost, smaller environmental impact, fast construction, easily scalable, and immunity to flooding (Wang et al., 2015; Xie et al., 2020). Owing to their massive size, VLFS are usually constructed by connecting multiple standardized modules with connector systems; thereby enabling easy construction and transportation. Moreover, a review of past research studies indicates that a monolithic floating structure has to resist enormous bending moments and shear forces that significantly increases the difficulty and complexity of structural design. A connector system is a critical component in the modularized floating structure and should be handled with caution. Many connector designs have been developed and comprehensive research studies were performed on a wide range of connector systems. In this paper, various design concepts for connector systems are first described and categorized according to their working principles. Recent research studies on hydro-elastic responses and structural integrity are then introduced. In addition, the determination of connector stiffness in practical designs is discussed, and suggestions for future engineering practice are provided.

2. TYPES OF CONNECTOR SYSTEMS

2.1 General

The relative motion between adjacent VLFS modules consists of six components, grouped into translational motions (surge, sway and heave) and rotational motions (pitch, roll and yaw), as shown in Figure 1. Each degree of freedom (DOF) can be rigidly restrained, compliant or fully released. A single connector is usually designed to be compliant to restrain the translational DOF to some extent, and connector systems deployed in VLFS are commonly composed of multiple compliant connectors to restrain more DOFs, as illustrated in Table 1. It can be further inferred that a three-dimensional combination of multiple connectors generally results in a connector system with no unrestrained DOF, denoted as "all-restrained" connector system herein. For instance, VLFS modules connected with horizontal and vertical elements at both short and long sides ideally allow no relative motions. In practice, the margin in each individual connector determines the possible relative motions, and the stiffness of the connector system depends on connector numbers, configurations and materials used.

Table 2 compares the key positive and negative aspects of rigid and flexible connector systems. In general, a flexible connector system results in lower connection forces and easier decoupling procedures. By varying the stiffness of individual connectors, the "all-restrained" connector system transits from a fully rigid connection to a fully flexible connection. Connector systems for modules connected with no gap may be categorized into three main types: rigid, semi-rigid and hinge connector systems. A rigid connector system commonly consists of a combination of multiple connectors, whereas a hinge connector system is realized with discrete connectors such as a hinge, a ball joint, and others. The main difference between rigid and hinge connections lies in the transmitted bending moment. The largest action effects in a hinged connector will be the axial and shear forces, while the transmitted moments are negligible. No distinct boundary exists between the rigid and semi-rigid connector systems, but the latter option has a relatively smaller stiffness. Some other connector systems are designed for floating modules with spaces in between, and they include rigid, vertical-free, hinge and flexible connectors.

2.2 Connector Systems for Floating Modules Connected with No Gap

The motions of VLFS are permitted to be within an allowable range. According to various construction principles, alternative design concepts are adopted in developing an "all-restrained" connector system. Table 3 presents typical examples of connector systems developed based on: (1) cable "tensioning", whereby multiple modules are prestressed with cables or bars; (2) hinge "clicking", whereby adjacent elements are clicked together with multiple hinges in different DOFs; and (3) tooth "anchoring", whereby toothed structures are connected with a steel pin.

Cable "tensioning" connector system is used to connect floating modules by passing and tensioning cables (or tendons) through internal ducts, by which a larger stiffness can be achieved. This tensioning principle generates well distributed connection forces, but the shear resistance to heave motions could be weak. Hence shear keys may be installed to take care of the transverse shear forces. In practice, cables are not grouted to the sleeves to facilitate future removal when necessary. The cost of cable "tensioning" connector system is low, but the prestressing tendons may have to be destroyed to disassemble the floating structure, and a large part of the connector system will have to be renewed for future repurposing of the floating structure. Rognaas et al. (2001) designed a special connector with steel cables to handle axial tensile forces and hydraulic jacks and elastomeric bearings to provide elastic supports (see Table 3a). The cable compliant technology was also used by Halim to combine adjacent floating modules with different prestressing cable configurations (Table 3b). When the modules are connected only at the upper deck level, this connector system does not effectively transfer internal moments. However, when prestressing cables are arranged at both upper and lower deck levels, flexural resistance can be provided to some extent and the bottom opening scenarios are eliminated (Jiang et al., 2018). The cable "tensioning" connector system has been successfully applied in the Incheon Floating Pier (Table 3c) in 2018 and it has shown good in-service performance so far (Jung et al., 2019). Each fabricated prestressed concrete segment has many connection holes for prestressing bars around the cross section, and double rubber layers were also attached to prevent water penetration during the module connection work. These connection holes were made in advance in the segment fabrication work and closed by temporary rubber water stoppers during the launching of the segment. The stoppers were removed one by one before inserting prestressing bars into the connection holes. All segments were connected to each other by prestressing bars on the sea to form the 200 m long sub-module.

Hinge "clicking" connector system is developed with multiple rows of steel piano hinges either in horizontal or vertical alignments. Key protruding steel connections are externally distributed over the sides of the floating module to reduce point load intensity and increase the rigidity. Armin's connector design (Table 3d) uses steel piano hinges distributed at both top and bottom sides to guarantee sufficient stiffness and effectively transfer bending moments; thereby forming a rigid connector system (Lei, 2007). In contrast, Han's connection (Table 3e) and McDermotts Mobile Offshore Base (MOB) connection (Table 3f) has only one row of hinge connectors and thus they may be considered as a hinge connector system with angular rotations allowed in service (Lei, 2007; Mcallister, 1997). In Armin's design, the lower edges of the joined pontoons tend to open up in sagging condition because the pins are placed only on the deck level, thus tolerance control for the locking pin's holes position is very crucial. When compared to the cable "tensioning" system, steel hinge connections are relatively expensive and are easily damaged in severe sea conditions due to fatigue and durability issues. Besides, it is difficult for inspection or maintenance once steel piano hinges are clicked, thus the costs for replacement of the steel connectors would be high.

The tooth "anchoring" connector system is commonly made of protruding teeth attached on sides of adjacent floating modules, which are shoved or slid in place and locked by steel bars or bolts. The large protruding teeth are not easily damaged during coupling, but may hinder the coupling procedure. Bolting technology requires regular monitoring of the bolt torque as it may loosen over time. The tooth "anchoring" connector system is able to bear high internal force in service and it is rather easy for disassembling the floating modules by pulling out the steel bar. Bargeco's connector design (Table 3g) consists of male and female coupling members that can connected with a wedge engagement (Yoon and Boldbaatar, 2013). Similarly, Gardner's design (Table 3h) aligns adjacent pontoons with two coupling members and an elongated connecting member fitting into a recess. Both connector designs have limited tensile strength and require high tolerance control for assembly. Bargeco's connector demands the mating modules to be even and heel perfectly, which is not practical and may only suitable for calm water condition. Gardner's design can lock both top and bottom of the connector theoretically, but it is hard to achieve in practice because of tolerances of components and assembly. Tooth "anchoring" technique has been practically used in the connecting system of Floating Performance Stage at the Marina Bay in Singapore. A special square-shaped connector unit made of high tensile steel is designed to connect to the corners of four surrounding floating platforms (Wang et al., 2015). The hollow edges of the connector unit slip into the tapered wedges, and coupling members are kept in place by twelve distributed detachable steel locking pins. The connector system that eventuated required the pontoon modules to be joined at the corners using a floating corner connector and along the mating edges with side connectors (5 along the longer edge and 2 along the shorter edge) (Table 3i). In general, the tooth "anchoring" connector system can be very stiff when subjected to transverse compression, but gaps are needed to insert the steel bar during the coupling process.

Figure 2 shows some other connector systems that use bolts or bars to lock adjacent modules without protruding teeth. Au-Yeong proposed connector assemblies that comprise two housings mounted on adjacent floating modules and one movable connector element, as shown in Figure 2a. The connection is established by shifting the connector element from one housing to the other and securing it by horizontal latches at the top and vertical pins at the bottom. In practice, the tolerance between the latch pin and hole has to be large enough for successfully latching all the connector elements with housings, which may result in loose connection and creates gap movements between adjacent modules. A special type of rigid connector system, known as Frictional Locking Connector, was developed by Han-Ocean (Yoon and Boldbaatar, 2013), in which locking bars were dropped in directed recesses of the two coupling parts to secure the connection between floating units. Both designs avoid shoving or sliding of protruding teeth, but a high tolerance control is required for the assembly. Wilkins (2002) patented a connector system with tapered fingers attached on floating modules, as shown in Figure 2c. The male finger assembly includes a casing configured with a camshaft, cams, and connector bodies. The cams are scalloped to prevent the connector bodies from turning the camshafts when they are under loads in a locked position. A similar casing configuration with no moving parts is used for the female finger assembly. Female fingers are preferably placed along one side of the floating module and separated enough so that a male finger may fit flush within the two female fingers.

As described above, tooth "anchoring" connector systems can be very strong in resisting transverse compression, but they have limited tensile resistance and require high tolerances during the coupling process. In order to overcome this, a new design of rigid connector system, hereby termed "Prestressed Concrete Shear Key Connection (PCSKC)", has been developed by the authors. The proposed connection combines the use of tooth "anchoring" and cable "tensioning" approaches. Figure 3 illustrates the proposed PCSKC for the connection of two-modular concrete floating structures. The adjacent floating modules are designed with thicker side walls and connected with prestressed bars at both the top and bottom of the modules, which resist axial tensile forces and provide flexural moment resistance. Shear keys (Figure 3b) are arranged along the interface between two modules to withstand vertical shear forces. The assembly of floating modules using PCSKC requires little tolerance to be provided for installation purpose. In addition, the connection stiffness can be adjusted by varying the shear key arrangements, amount of prestressed bars as well as prestressing forces.

2.3 Connector Systems for Floating Modules with Space in Between

In engineering practices, large floating structures are occasionally made of several modules with space in between so as to improve mobility. In such cases, the rigidity of connector systems is designed in accordance with different practical situations, including rigid connector system, vertical-free connector system, hinge connector system and fully flexible connector system. For instance, the US Navy's Mobile Offshore Base (MOB) platform requires rigid connected modules to accommodate aircraft take-off and landing, whilst fully flexible connector systems that allow sway or surge motions are used for transport reasons, e.g. ducts, cables, or pedestrian bridges connecting to shore.

Brown and Root designed a rigid connector system that combines semi-submersible modules in MOB based on in-operation Tension Leg Platform (TLP) connections and ABB Vetco Grey latching system (Ramsamooj and Shugar, 2002). Figure 4 shows the conceptual design of rigidly connected semi-submersible MOB modules and latching interface. Each connector comprises male and female halves, made of thin-walled steel tubing. Each half pivots on a 3.66 m diameter tube, and is able to move or slide on the pivot tube via hydraulic cylinders.

Vertical-free connector systems, as shown in Figure 5, are used when surge and sway motions are to be prevented. They can be categorized as “rotation allowing” and “rotation restricting” connections. The vertical-free rotation-free connection (Figure 5a) is made of tubes and rods with horizontal transverse bolts/pens and fixed holes. The sway motion is prevented by clamping the connection elements in the horizontal plane, while the heave motion is allowed since only one set of tubes and rods is used in the horizontal plane. The vertical-free rotation-resistant connection (Figure 5b) uses tubes and rods with horizontal transverse bolts/pens with ends sliding in vertical slots. Diagonal connection elements are used in both horizontal and vertical planes, which can effectively restrict the rotational motions. In a similar manner, hinge connector systems can be realised by using horizontal transverse bolt/pen connections as shown in Figure 6.

Flexible connector system is used where floating structures are moored and other relative movements are allowed. Xu et al. (2014) proposed a conceptual design of flexible connector with trapezoidal rubbers and cables, as illustrated in Figure 7. The rubber was mainly used to constrain the longitudinal motion between adjacent modules when compression forces occur. The cable is used to constrain the longitudinal motion between adjacent modules when tension forces occur. Very limited moment and shear force resistances can be provided by such a flexible connector system.

3. RESEARCH STUDIES ON CONNECTOR SYSTEMS

3.1 Hydroelasticity Theories and Analysis Approaches

VLFS behaves elastically under wave actions because of its large horizontal dimensions as compared to the wavelength, and its small bending rigidity. The response of VLFS cannot be solely described by rigid body motions using conventional hydrodynamic analysis, as the interaction between elastic deformations and the surrounding flow field must be taken into account. Furthermore, for VLFS consisting of multiple interconnected floating modules, the hydroelastic response directly affects the nature and magnitude of internal forces acting on the connectors as well as the overall structural integrity. Thus, a study based on hydroelasticity is essential to verify the serviceability and strength of VLFS.

Figure 8 presents an overall view of theories, numerical methods and physical models for the performance evaluation of VLFS. The hydroelastic behavior has been thoroughly studied for ships and floating structures employing potential flow solvers based on: (i) two-dimensional (2D) linear theories (Betts et al., 1977; Bishop and Price, 1977; Jørgen and Mansour, 2002); (ii) 2D nonlinear theories (Juncher and Terndrup, 1979); (iii) three-dimensional (3D) linear theories (Bishop et al., 1986); and (iv) 3D nonlinear theories (Wu et al., 1997; Chen et al., 2003; Chen et al., 2006; Lee et al., 2016). VLFS is frequently simplified as a floating beam or a floating plate model in the analysis, and hydroelastic formulations have been developed through the application of strip theory and Green's function method (Fu et al., 2007). In order to reduce computational effort and time, hydroelastic analysis is commonly carried out in the frequency domain by assuming a linear response. Nonlinear quadratic strip theories formulated in the frequency domain may be used to predict wave loads and structure responses in moderate seas (Juncher and Terndrup, 1979).

When nonlinear characteristics of the fluid and structure are taken into consideration or when transient responses are of concern, the frequency domain analysis is not applicable. This happens in some situations such as slamming impact pressures and excessive structural deformations due to airplane landings/take-offs. Under such circumstances, the time domain approach is necessary for solution but it requires intensive computational costs (Feng and Bai, 2017; Nematbakhsh et al., 2017). Commonly-used approaches for the time domain analysis of VLFS includes the direct integration method (Watanabe et al., 1998; Liu, and Sakai, 2002) and the Fourier transform method (Kashiwagi, 2000; Kashiwagi, 2004; Endo, 2000; Ohmatsu, 2005). Liu and Sakai (2002) developed a hybrid approach, by which the boundary element method (BEM) is used to evaluate the fluid motion while the finite element method (FEM) is to calculate the elastic deformation of the floating structure.

Kashiwagi (2004) used the time-domain mode-expansion method to assess additional drag forces on airplane due to elastic deformation of the floating runway. Wu and Cui (2009) elucidated various 3D hydroelasticity theories ranging from linear frequency domain analyses to nonlinear time domain analyses. Comparisons between frequency domain and time domain solutions indicated that discrepancies exist for the case of anti-symmetric responses, where time-domain analyses agree better with experimental measurements (Kim et al. 2009). It is worth mentioning that the computational fluid dynamic (CFD) has gained popularity because of its accurate representation of Navier-Stokes equations and ability to handle viscous effects and vortex formations, but intensive computational costs are required (Wang and Tay, 2011; Lee et al., 2003; Lakshmynarayanana and Temarel, 2019). CFD method will not described in detail herein.

Two main numerical methods have been developed to implement the hydroelastic analysis: direct method and mode superposition method. In the direct method, one solves the equation of motion directly with all nodes of the discretized structural system (Namba and Ohkusu, 1999; Khabakhpasheva and Korobkin, 2002; Taylor, 2007; Ohkusu and Namba, 2004; Kim et al., 2007). In particular, Kashiwagi (1998a, b) used the B-spline function to represent both the wave pressure and the elastic deflections. The mode superposition method introduces the generalized flexible modes apart from six rigid-body modes to describe the structural deformations and decomposes the hydroelastic problem into diffraction and radiation problems for each mode (Wu et al., 1995; Senjanovic et al., 2008). The generalized flexible modes require the determination of corresponding mode shapes of VLFS, which can be achieved through either analytical modal functions or FEM eigenvalue analysis. While analytical solutions are only available for structures with simple geometries (Bishop and Price, 1979; Newman, 1994), the FEM approach is capable of modeling structures with complex geometries or assembled by connecting floating modules. Moreover, FEM eigenvalue analysis is able to consider symmetric and anti-symmetric modes simultaneously, as well as 3D structural deformations.

The mode superposition method can be further divided into "wet" mode (Loukogeorgaki et al., 2012) and "dry" mode (Fu et al., 2007; Loukogeorgaki et al. 2008) approaches depending on whether the surrounding fluid effect (added mass and hydrostatic-gravitational stiffness) is taken into account in the calculation of VLFS mode shapes. The "wet" mode approach can be more computationally expensive with the inclusion of the surrounding fluid effect. However, dynamic characteristics calculated from the “wet” mode approach can represent the real physical problem better by correctly considering the total mass and stiffness matrices. In addition, the coupling between the ‘dry’ mode shapes of the rigid body modes and the generalized flexible modes, as well as of the generalized flexible modes themselves can be considered when computing the ‘wet’ mode shapes (Loukogeorgaki et al., 2012). It is noted that the utilization of analytical modal functions is considered as a ‘‘dry’’ mode approach, while the FEM eigenvalue analysis can be applied in either the ‘‘dry’’ mode approach (Riggs et al., 2000; Fu et al., 2005; Senjanovic et al., 2008a; Senjanovic et al., 2008b) or the ‘‘wet’’ mode approach (Michailides et al., 2013).

In practice, VLFS are usually constructed by connecting multiple standardized modules with connector systems from the viewpoints of easy construction, transportation and deployment (Watanabe et al., 2004). The effect of both flexibility of the structure and the existence of the connectors should be considered to properly evaluate the hydroelastic performance of interconnected multi-modular VLFS. Both floating modules and connector systems can be modelled as either rigid or flexible (including hinges) in the hydroelastic analysis, resulting in four main types of model: rigid module and rigid connector (RMRC), rigid module and flexible connector (RMFC), flexible module and rigid connector (FMRC) and flexible module and flexible connector (FMFC) (Fu et al., 2007). In particular, RMFC model was used by many researchers to predict the hydroelastic responses of VLFS (Wang et al., 1991; Riggs and Ertekin, 1993; Riggs et al., 1999; Wei et al., 2017; Wei et al., 2018).

Riggs et al. (2000) compared the use of RMFC and FMFC models in hydroelastic analysis, and found that the effect of module elasticity in the FMFC model can be reproduced in a RMFC model by changing the connection stiffness to match the natural frequencies and mode shapes of the two models. To study hinge-connected floating structures with the modal superposition method, Newman (1997) defined hinge rigid body modes to represent relative motions between floating modules. When the direct method is employed, translational and rotational stiffness are specified for connector systems at the continuity point of interconnected floating modules, and structural mass and stiffness matrices are updated accordingly. For simple hinge connections, rotational stiffness is set to be zero.

In the past two decades, the RMFC model has been adopted by many Chinese researchers to predict hydrodynamic responses and connector loads of VLFS. Wang et al. (2002) developed a time sequence analysis method based on the assumption of rigid modules and flexible connectors to study the linear wave-induced response of MOB. Yu et al. (2003; 2004) used RMFC model to study the dynamic responses of MOB connectors and further investigate the effects of connector stiffness, multiple modules interaction, wave angles and sea states on the MOB module motions and connector loads. Yu et al. (2006a; 2006b) applied RMFC model to determine the hydrodynamic responses of the floating trestle in seawaters with finite depth, which were further verified by comparing with spectrometric analysis result and the experimental test result. Liu et al. (2014) further adopted the RMFC model to analyze the dynamic responses of connectors in VLFS with a shallow draft and concluded that the shallow water effect may increase relative motions between floating modules, leading to a higher vertical connector load intensity.

Experimental investigations related to interconnected floating modules based on scaled physical models are necessary to practically assess the overall performance and forces in the connector system, and also to verify numerical analysis approaches (Diamantoulaki et al., 2008). Martinelli et al. (2008) carried out 3D experimental tests on I-shaped and J-shaped floating modules connected with tie rods to study effects of module layout and wave obliqueness on the effectiveness of floating breakwaters. Peña et al. (2011) and Ferreras et al. (2014) implemented experimental investigations on π-type floating modules that are connected with flexible connectors (steel cables through cylindrical neoprene) to explore the connectors' forces of VLFS, including horizontal and vertical shear forces and associated moments. Loukogeorgaki et al. (2014) performed 3D experimental tests on an array of multiple floating box-type modules connected with flexible connectors (coated wire rope) to assess connectors' internal forces under the action of both regular and irregular perpendicular and oblique incident waves. Ding et al. (2019) performed model tests on a 3-module VLFS and an 8-module semi-submersible-type VLFS in two simulated shallow sea regions to investigate the hydroelastic responses of VLFS deployed near islands and reefs in shallow sea. The aforementioned physical model studies effectively evaluate the influences of module geometries, environmental conditions and connection types on structural responses and connecting forces, and also helps to verify analytical and numerical solutions.

3.2 Hydroelastic Responses

VLFS is required to satisfy the functional and operational requirements in practice, such as tolerance on the structure motions and structural internal forces. All these criteria are directly related to the hydroelastic response, and it is desirable to reduce the response magnitude as much as possible to ensure the safety and serviceability of VLFS.

Many research studies have been performed to evaluate the effect of the connector characteristics on the hydroelastic response of VLFS considering either hinge-type connectors (Lee and Newman, 2000; Xia et al., 2000) or flexible connectors (Fu et al., 2007; Loukogeorgaki et al., 2012). The main responses discussed herein are: (i) vertical deflections; and (ii) internal forces. Lee and Newman (2000) and Teng et al. (2014) investigated rigid floating modules inter-connected with hinge connectors, while Yoon et al. (2014) and Zhao et al. (2015) evaluated the performance of flexible floating modules connected with hinged joints.

Figure 9 shows dimensionless vertical deflection and bending moments of floating plate structures with multiple hinge connections, obtained by Yoon et al. (2014) who used the hybrid BEM-FEM method. As the number of hinge connections increases, vertical deflections in the floating plate increase and peak values occur at hinge connections, while bending moments reduce in general and maximum values locate around the centre between adjacent hinges. Note that maximum moment of single-hinge plate is larger than that of the monolithic plate, indicating that the use of hinge connections is not always beneficial in reducing the maximum bending moment.

Riggs et al. (2000) implemented hydroelastic analysis of VLFS consisting of rigid modules interconnected with flexible connectors, while Fu et al. (2007) used 3D linear hydroelastic theory to predict the response of flexible floating modules interconnected with flexible connectors. Figure 10 presents vertical deflection profiles and bending moments of a flexible floating plate interconnected with flexible connectors for different rotational stiffness (k_{rot}) (Riggs et al., 2000). In the figure, w represents the calculated deflection value, while symbol, A, in the y axis indicates wave amplitude, where $A = H/2$, and H is the wave height. It is seen that the vertical displacement amplitude decreases as the rotational stiffness increases and the deflection profile of the floating plate interconnected with stiffer connectors approaches the experimental results of continuous structures. Also, the rotational stiffness of the connector system has a greater effect on the regions near the connector. In terms of bending moments, the value at the connector system gradually decreases to zero as the rotational stiffness reduces. On the other hand, the bending moment within the upstream and downstream modules will increase slightly.

Xia et al. (2000) evaluated the hydroelastic behaviour of articulated plates interconnected with vertical and rotational springs with a variation of stiffness value from zero to infinity that represent welded joints during the assembling process. The displacement at the connectors is found to be larger than that on the plate, and an increase in the spring stiffness is favourable in reducing the connector motions. The bending moments and shear forces at the connectors are independent of the stiffness of the vertical and rotational springs, respectively.

In the aforementioned studies, the number and stiffness values of connections are artificially specified by researchers. Wang et al. (2009) and Riyansyah et al. (2010) proposed the use of a compliance parameter χ (defined in Equation (1)) in determining the optimal rotational stiffness parameter, ξ, and number of semi-rigid connectors, n, to minimize the hydroelastic responses of longish VLFS. A minimum value of compliance parameter is desirable and it is equivalent to a stiff beam acting against wave action.

$$\chi = \frac{1}{A\rho L}\int_{-L/2}^{L/2} |p||w|\,dx \tag{1}$$

where A is the wave amplitude, ρ the mass density of water, L the floating beam length, p the hydrodynamic pressure, and w the deflection of the floating beam. Figure 11 compares hydroelastic responses of floating beams with multiple optimally designed semi-rigid connections and with rigid connections. Semi-rigid connections with appropriate stiffness and inserted at suitable locations are found to be more effective in reducing the vertical displacement as compared with rigid or hinge connections. The compliance parameter was observed to reduce by using a moderate number of connector systems, i.e., n=3–7. Further increase in number of connections does not result in a significant reduction in the value of the compliance parameter.

3.3 Internal Forces in Connectors

The structural integrity of VLFS under wave action strongly depends on the induced internal forces in the connectors. Up to now, limited research studies had been carried out on the numerical evaluation of the internal forces and effects of various design parameters, such as stiffness of connectors, module layout, shallow water effect and incident wave period (Kim et al., 2007; Liu et al., 2014; Michailides et al., 2013; Newman, 1997; Qi et al., 2017; Yu et al., 2003; Yu et al., 2004).

Past research studies indicate that rigid connectors generally lead to high load intensity, whilst the use of hinge connectors can effectively reduce the magnitude of connecting forces (Gao et al., 2011; Gao et al., 2013; Dai et al., 2018; Jiang et al., 2019). Therefore, connector systems with a certain degree of flexibility are usually adopted in designs of VLFS. Specifically, Newman (1997) computed the shear forces acting on the hinge connectors of floating structures, and analysed the influence of the number of floating modules on the forces in hinge connectors. On the other hand, Kim et al. (2007) evaluated the bending moments and the shear forces at flexible connections of VLFS assembled of modules, and concluded that the internal forces in connectors of side-by-side arranged VLFS modules generally increase as the connection stiffness and heading angle increase. Qi et al. (2017) studied the relationship between the connector load and rigidity by computing the dynamic responses of flexible connectors in a VLFS with different combinations of transverse, longitudinal and vertical rigidities. Analysis results show that whether the transverse rigidity is high or low, there exists a combination of longitudinal and vertical rigidity that results in the peak connector load. Zhao et al. (2019 further provided optimal stiffness values in three directions of flexible connectors for multi-modular floating systems in different sea conditions.

Apart from the connector stiffness, incident wave characteristics also cause significant effects on connector forces of VLFS. Yu et al. (2003; 2004) conducted numerical analyses of MOB connector loads on the basis of a RMFC model. The results indicate that the longitudinal connector loads are much larger than the lateral and vertical loads. Besides, the wave headings significantly affected the forces between modules, and the longitudinal load of the connector reached its maximum with a 75° wave direction. It is suggested to keep the angle between the MOB and wave direction less than 45° and to avoid unrealistically large connector loads.

Ding et al. (2019) performed a model test on an 8-module semi-submersible-type VLFS with specified connector stiffness of 4.60×10^6 N/m, 6.55×10^6 N/m and 9.78×10^6 N/m in three directions. Figure 12 presents the variations of connecting forces along the length of the VLFS model from connectors C1, C3 to C13. Three frequencies representing short, medium and long regular waves, that is, 0.897 rad/s ($T = 7$ s), 0.483 rad/s ($T = 13$ s) and 0.209 rad/s ($T = 30$ s) were considered. The distribution of internal forces is significantly dependent on the frequency of incoming waves. Axial forces, F_x, for connectors in the middle of the longish VLFS are generally greater than those at the two end parts, but no consistent pattern is observed for shear forces, F_y.

Loukogeorgaki et al. (2014) implemented 3D experiments to assess the internal forces in connectors of multiple floating box-type modules with flexible connectors, under wave actions of different characteristics (wave obliquity, wave period and wave height). Figure 13 shows the variation of internal forces with the change of incident wave frequency and wave steepness. Test results showed that the wave obliquity and wave height affect forces mainly in the low frequency range (6 rad/s < ω < 9 rad/s). Contrary to Ding's findings, it is seen from Figure 13 that the increase in incident wave frequency generally leads to the decrease in axial and shear forces, which may attribute to a relatively higher wave frequency and a shorter structural length. Besides, the increase in incident wave steepness (H/L) results in the increase of these forces, especially in the low frequency range. For the same wave height and period, the increase of wave obliquity from 60° to 90° leads to a decrease in internal forces, resulting in a more efficient floating structure in terms of both functionality and structural integrity.

Most research studies were conducted on VLFS with modules connected in the transverse direction only. Michailides et al. (2013) considered VLFS consisting of a grid of floating modules flexibly connected in two directions, and identified the optimal module layout and connectors' rotational stiffness. Figure 14 presents the variation of connector internal forces as a function of incident wave frequencies for a 3×3 grid type floating structure with wave angle β = 0°. The increase in connector rotational stiffness from K_{R1} and K_{R2} to K_{R3} results in a decrease of the peak axial forces and shear forces. Additionally, a larger rotational stiffness K_{R3} leads to larger moments in X direction, $M_{y,Xc}$。

Figure 15 compares the axial forces in X direction, $F_{x,Xc}$ as a function of incident wave frequency for different module layout and various rotational stiffness values. The change of the module number and layout directly affects connectors' internal loads. Specifically, a 1 × 2 grid structure has the largest maximum axial force, $F_{x,Xc}$, compared to structures with other grid layouts. For all cases, the axial forces $F_{x,Xc}$ was the same and small regardless of connector stiffness when the incident wave frequency $\omega \geq 2.72$ rad/s.

To further investigate the application of a combination of hinge and rigid connectors in floating structures and their effects on the connector forces, a comprehensive experimental model test program was conducted by the authors at the National University of Singapore (NUS) Hydraulics Laboratory. Figure 16a shows three floating module layouts tested in the wave basin, including one-line system, 2 × 4 grid system and 3 × 3 grid system. In the one-line system, two proposed connector types (rigid or hinge) were applied for the outermost connector. Similarly, rigid and hinge connector systems were explored in 2 × 4 and 3 × 3 grid module layouts as described in Figure 16a. Note that the first two modules in the one-line system served as “a floating bridge” to connect the longish floating structure with the onshore quay boundary. Figure 16 b–d presents the maximum bending moments of three module layouts under 100-year irregular wave with a heading angle of 0 degree. In general, the moments can be effectively reduced with the use of hinge connectors, especially for 2 × 4 and 3 × 3 grid systems. However, the motions of the hinge-connected systems were relatively larger, thus a trade-off needs to be considered between connecting loads and structural motions in the design of connector system. In addition, a longish VLFS (one-line system) may sustain larger connecting forces compared to the floating structure with smaller length-to-width ratios (that is, 2 × 4 and 3 × 3 grid systems).

Liu et al. (2014) studied the shallow water effect on the dynamic characteristics of connectors. It shows that the vertical connector load tends to be amplified for a VLFS with a shallow draft, which should be considered in the engineering design practice. Gu et al. (2015) used the time domain method to determine the connector loads for a VLFS under the combined action of wave loads and ship impact loads. Under impact loads, high-frequency oscillations in the time history curve of the connector load are observed. Under different wave headings, the maximum magnitude of the connector load is found to occur in the X direction. An oscillatory connector load is observed in the Y direction with a wave heading of 75°.

3.4 DISCUSSION

3.4.1 Determination of Connector Stiffness

Assessment of hydroelastic responses combined with determination of connector forces represents a key element towards an integrated design of VLFS. Based on extensive review work presented above, it is concluded that various factors significantly affect the performance of VLFS in terms of operational design requirements and structural integrity. These include the variation in connector stiffness, geometrical dimensions, and grid type of floating structures and wave field characteristics (that is, wave obliquity, wave period, wave height, etc.), of which the connection stiffness is particularly important.

In general, the use of rigid connector systems induces relatively smaller structural motions but extremely higher internal loads when compared to hinge connectors. To achieve a balance between load and motion responses, flexible connectors that utilize compliant materials such as rubber, spring, and cable, have been used in practice. However, this results in complex connector system and design, and raises difficulties in quantifying the stiffness accurately, apart from referring it as a semi-rigid connector system. Meanwhile, in the evaluation of hydroelastic responses and connecting forces in VLFS with flexible connectors, researchers usually artificially specify the translational and rotational stiffness from zero to infinity, regardless of their feasibility of the connector system. Under such circumstances, there is a gap between the results of hydroelasticity research and the development of practical connector systems. As part of critical design variables of VLFS, connector characteristics should be defined and selected to satisfy the design objective and operational requirements.

Experimental test is an effective way to determine the actual stiffness of a practical VLFS connector system via the load-deformation relationship. China Ship Scientific Research Center has conducted extensive experimental research studies on the strength and behavior of various practical connector systems. Qi et al. (2015) designed a flexible connector system for VLFS with a shallow draft, which is composed of 5 ball-and-spring devices (2 devices in the x direction, 2 devices in the z direction and 1 device in the y direction), as shown in Figure 17. Comprehensive static and dynamic load tests were performed to study the rigidity and evaluate the structural safety of the connector design. Test results indicated that the relationship between load and deformation of the flexible connector system remains in the linear range during the test, from which the stiffness value can be obtained. Besides, different load combinations may result in uneven deformations in the 2 ball-and-spring devices in the x direction, which requires special attention in the design. Zhang et al. (2019) explored the use of nylon and rubber materials in the design of a flexible connector. Mechanical properties of the connector system were determined from experimental tests, from which a nonlinear relationship between the load and displacement was observed. The stiffness characteristics and stress magnitudes are found to be significantly influenced by nylon and rubber material properties, which needs to be optimized in the engineering design practice.

In the case that the test data of VLFS connector is unavailable, engineers are required to use reasonable stiffness values in the design. Figure 18 shows the flow chart proposed by the authors to determine the connector stiffness for practical designs. The process includes two main parts:

hydroelastic analysis and structural analysis. First, the connector stiffness values are assumed according to its characteristics. For instance, the rotational stiffness can be set as a large value for near-rigid connectors, whereas it should be set small for near-hinge connectors. For the translational stiffness, Zhao et al. (2019) has studied the optimal stiffness layout of modularized floating structures using genetic-algorithm-based approach and concluded that the stiffness along the surge motion should be designed relatively soft while the stiffness along the sway and heave motions should be designed relatively hard against shear load. The suggested optimized stiffness in three directions are $k_x = 10^6$ N/m, $k_y = 10^{11}$ N/m and $k_z = 10^{11}$ N/m (where x, y and z represent surge, sway and heave, respectively), which can be used as initial values if no other information is available. With the assumed connector stiffness, and in conjunction with wave field characteristics and structural geometry information, the hydroelastic analysis can be performed on the VLFS to obtain the connector internal forces. Next, a detailed finite element model of the connector systems needs to be established to perform the deformation analysis with the inputs of connector geometries, material properties and connecting forces. The relations between the loading and deformation response are obtained, from which the connector stiffness can be inferred. If this differs from the initial assumed value, the hydroelastic analysis will be carried out for a second round with the obtained stiffness, and the iteration ends when the stiffnesses converge. Shi et al. (2018) claimed that the connector stiffness is related to connecting forces and material nonlinearity, thus several rounds may be needed in the iterative procedure to finalize the actual stiffness values. As the by-product, the strength analysis can also be carried out using the detailed finite element model to check the safety of the connector design under maximum internal loads.

3.4.2 Fatigue Strength

Connector systems of VLFS are subjected to repeated loading conditions throughout the service life due to the cyclic nature of environmental loads, which may result in serious fatigue problems. Although extensive research studies on fatigue analysis and design of marine structures have been conducted, very limited literature were found on fatigue behavior of connector systems specifically (Lotsberg, I. 2016). Ramsamooj et al. (2001; 2002) developed an analytical model to predict the fracture-based fatigue life of VLFS connectors under random wave actions in the marine environment. Besides, a performance function is further defined in terms of the material properties, nominal stress range and inherent defect or starter crack to perform the reliability-based design analysis of the fatigue life of the connectors in MOB. The reliability calculations indicated that relatively lower stress values should be used in the design to meet the fatigue life target reliability level. Wang et al. (2009) predicted the fatigue behavior of the connectors in a floating bridge with employing the local stress–strain approach. It is revealed that the ultimate tensile strength and the sequence of the dynamic loads may significantly influence the fatigue damage of the connectors. More research studies are expected to ensure the safety and economical design of connector systems for VLFS.

The China Ship Scientific Research Center studied the fatigue strength of various VLFS connector systems in recent years. Liu (2014) utilized the S-N curve method and theory of fracture mechanics to predict the fatigue life of a connector system. Seven S-N curves were considered, and the effects of wave angles and sea states on the fatigue damage were analyzed. Single-stage Paris law and two-stage Paris law were adopted to calculate the fatigue life of connectors with an initial crack of thirty different sets of sizes and shapes. It is concluded that smaller initial cracks generally lead to slower crack growth speed and longer fatigue life of the connectors. Qi et al. (2017) conducted a model test of a hinge connector, consisting of a nylon sandwich and a pipe shaft strengthened by circular frames to evaluate the fatigue strength and structural stresses of the connector. The fatigue life was evaluated based on theory of the S-N curve and crack propagation separately. The fatigue life and fatigue strength are found to be significantly affected by the load magnitude and wave angle. Zhao et al. (2018) carried out an experimental study on the ultimate strength of the VLFS connector foundation support reinforcing area structure under complex loads. Plastic hinges were observed in the model when subjected to large combined vertical and longitudinal loads. Therefore, the material nonlinearity may be important and should be considered in the analysis and design of connector systems for VLFS.

3.4.3 Active-control Connector System

Since the structural responses and connector forces of modularized VLFS are significantly affected by connector stiffness, Xia et al. (2016) proposed a special active-control connector system with air-springs. The connector stiffness could be adjusted along with the evolution of wave conditions by changing the air pressure inside the air-spring to reduce the oscillation of floating structures.

Figure 19a presents adjacent floating modules connected with two parallel air-springs, where symbols δ_1 and δ_2 represent respectively the initial horizontal and vertical distances between two modules. The air-spring configuration is shown in Figure 19b. An in/outlet is reserved for inflating or deflating the air-spring, and rubber bumper is used to cushion the hard impact due to extreme motion. Although the stiffness of connector can be altered by changing the air pressure, it is still difficult to accurately quantify the stiffness for practical design. Moreover, this special active-control connector system is also limited in terms of timeliness and complexity of the sensor signal transmission.

3.4.4 Materials Design of Connector System

Connector systems for VLFS can be designed with different materials such as steel, concrete and composites. The selection of appropriate materials relates to their own strength and advantages, functional requirements and application scenarios of floating structures. Considering its good mechanical properties and light weight, steel is suitable for connector systems in medium-scale floating structures that need to be transported from place to place, such as military pontoons, barges and causeways. On the other hand, concrete is resistant to seawater and keeps maintenance costs low, making it more attractive for connections in large permanent floating structures like breakwaters, piers and jetties.

In a seawater environment, a sophisticated connector system can be made of various materials to meet different requirements in practice. Conventional materials (steel and concrete) are commonly used for critical stiff components to ensure the structural integrity of VLFS once adjacent floating modules are joined. Rubber and foam are preferable for flexible components of the connector system to withstand impact loading and absorb kinetic energy of the moving modules, which can effectively dampen and gently decelerate the motion. In a sense, the use of the aforementioned two types of materials with distinctive mechanical properties fulfill two contradicting requirements on the elasticity and rigidity of the connector system. Additionally, steel cables or springs are occasionally used in the connection design to withstand axial tensile forces.

Fibre reinforced polymer (FRP) has been increasingly used in a variety of structures in the severe environments. FRP materials exhibit a linear-elastic behavior under tensile loading up to failure without showing any plastic behavior, owning higher tensile strength, but lower Young's modulus, than conventional steel. In general, carbon fibre reinforced polymer (CFRP) shows more favorable behaviors in terms of mechanical characteristics, chloride resistance and anti-moisture compared to FRPs manufactured of other materials, such as glass, aramid, and basalt (Sen et al. 1998a, b). Although no existing literature reported the use of CFRP in the connector system for VLFS, CFRP is a preferable substitute for the stiff component (steel block) and flexible component (steel cable) for anti-corrosion purposes. Specifically, ElSafty et al. (2014) evaluated the characteristics of prestressing carbon fiber composite cables (CFCC) in severe environment and concluded that CFCC showed excellent performance, maintaining very high guaranteed tensile strength retention and elastic modulus retention after conditioning for over 7,000 hours in an alkaline solution. Pantelides et al. (2003) reported that CFRP composites with their superior strength and resistance to electrochemical corrosion are a practical alternative for connecting precast concrete members in building structures. It is worth mentioning that mechanical properties, strength and stiffness of FRP decrease significantly with the increase of temperature (Fried, 1995). Therefore, the use of FRP may not be suitable where high temperature is of concern.

Durable connector systems that require less intrusive maintenance are highly desirable because it would exhibit longer life spans and thus maximize the use of the VLFS in the seawater environment. Ultrahigh performance concrete (UHPC) has roused great interests in the past decades due to its advantageous material properties, such as high strength, low permeability to water and chemical substance, good chloride penetration resistance, which is believed to have a broader application prospect in marine environments (Li et al., 2020; Shi et al., 2015; Wang et al., 2015). Similar as an FRP material, UHPC has not been applied in the connector system for VLFS at the current stage. However, this new advanced cementitious composite material has been widely used in the design and construction of connections for concrete bridge superstructures. Graybeal (2010) investigated the structural behavior of field-cast UHPC connections for modular bridge deck components via static and cyclic loading tests, and better performances were demonstrated than those of a conventional cast-in-place bridge deck. In Canada, 42 adjacent box-girder bridges were constructed with UHPC shear keys since 2008 (Rahman and McQuaker 2016). Yuan and Graybeal (2016) conducted full-scale tests on the UHPC joints when subjected to over 1 million load structural cycles and 10 thermal load cycles, and research results shown an enhanced strength of the connection filled with UHPC. Based on the experience in bridge engineering, UHPC can be a competitive material for the design of the stiff component (concrete block) in connector systems for VLFS.

3.4.5 Special Considerations

The integration of the wave energy converter (WEC) and VLFS has been conceptually studied by some researchers in recent years, which may bring benefits owing to space-sharing and multiple functions of the integrated system. Nguyen et al. (2019) proposed a raft WEC-type attachment that consists of multiple narrow pontoons connected to the fore of VLFS with hinge connectors and Power Take-Off (PTO) systems. The relative rotation between narrow pontoons and VLFS is utilized for power production, and the hydrodynamic responses of VLFS can be reduced simultaneously. Zhang et al. (2019) and Ren et al. (2019) suggested to embed PTO systems with connectors between adjacent floating modules to utilize the relative rotation for power production. Although no auxiliary pontoons are required for VLFS with embedded PTO systems between modules, the produced power should be limited due to stringent motion requirements of VLFS (e.g. the slope of a floating runway must be less than 1° (Suzuki, 2005)). Most of the studies on converting the wave energy from motions of connector systems for VLFS are still in the conceptual design stage, and several disadvantages has been reported, for example, the power capture factor of WEC-VLFS integrated system is limited for long wave conditions. Therefore, more research work needs to be further conducted to promote the development and maturity of this technique.

4. CONCLUDING REMARKS

In the next decade and beyond, we shall witness the construction of very large and sustainable floating platforms near congested coastal cities to create space on the adjacent water bodies for urban expansion. With the adoption of modular prefabricated construction approach for VLFS, the design and manufacturing of effective connector systems and careful construction control to safely connect segments on the sea is needed. A literature review on research and development in connector systems for modularized VLFS is presented. Key findings, potential design issues and suggestions for practice are summarized as follows:

1. Connector systems are categorized into cable "tensioning" connector, hinge "clicking" connector and tooth "anchoring" connector. By combining the tooth "anchoring" and cable "tensioning" technologies, a new design of connector system, PCSKC, is developed and presented herein for easy installation and stiffness adjustment.
2. Analysis based on hydroelasticity is crucial in the determination of structural responses and connector forces in modularized VLFS. The analysis is usually carried out in the frequency domain assuming linear response for easy computations. However, the time domain method has to be used when nonlinear characteristics of the fluid and structure or transient responses are of concern. Two main numerical methods, direct method and mode superposition method, have been developed for hydroelastic analysis. The latter method can be further divided into "wet" mode and "dry" mode approaches depending on whether the surrounding fluid effect is taken into account.

3. The effect of both flexibility of the structure and the existence of the connectors should be considered to properly evaluate hydroelastic performance of modularized VLFS. Both floating modules and connector systems may be modeled as either rigid or flexible. This results in four types of model: RMRC, RMFC, FMRC and FMFC. In particular, RMFC model was used by many researchers to predict the hydroelastic responses of VLFS, considering the flexibility of the connector system.
4. Rigid connectors generally lead to high internal forces, whilst hinge connectors can effectively reduce the connector forces. Thus, practical designs seldom adopt rigid connectors. As the number of hinge connections increases, vertical deflections increase and peak values occur at hinge connections, while bending moments reduce in general and maximum values occurs mid-way between adjacent hinges.
5. Semi-rigid connectors with appropriate stiffness and installed at suitable locations are found to be more effective in reducing structural responses when compared to fully rigid or hinge connections. Bending moments and shear forces at the connectors are independent of the stiffness of the connector system, respectively.
6. Besides connector stiffness, geometrical dimensions, grid type, and wave field characteristics also affect the magnitude of connector forces significantly. Hydroelastic analyses are required to assess the internal forces accounting for these parameters. In general, longish VLFS (one-line system) sustains larger connecting forces compared to floating structures with smaller length-to-width ratios.

7. The stiffness of the flexible connector is of upmost importance because it seriously affects the connector loads and dynamics of the floating platform. To address the inconsistency in the determination of connector stiffness between hydroelasticity research and development of practical connector systems, an iterative procedure is proposed herein to determine the actual stiffness of connector systems using both hydroelastic analysis and finite element structural analysis.
8. Current methods of analysis involve complicated mathematical models and techniques which are difficult to use. Simplified methods of analysis and models are in dire need for design practice.
9. CFRP and UHPC can be potential advanced materials in the design of connector systems for VLFS for the considerations of mechanical properties and durability.
10. More research studies need to be carried out on the fatigue behaviour of connector systems for VLFS to ensure the safety and economical design in the engineering practice.

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REFERENCES

Betts, C.V., Bishop, R.E.D. and Price W.G., 1977. The symmetric generalised fluid forces applied to a ship in a seaway. *Royal Institution of Naval Architects Supplementary Papers*. 199:265–78.

Bishop, R.E.D., and Price, W.G., 1977. The generalised antisymmetric fluid forces applied to a ship in a seaway. *International Shipbuilding Progress*. 24:3–14.

Bishop, R.E.D., and Price, W.G., 1979. Hydroelasticity of ships. Cambridge: Cambridge University Press.

Bishop R.E.D., Price, W.G. and Wu, Y., 1986. A general linear hydroelasticity theory of floating structures moving in a seaway. *Philos. Trans. R. Soc. Lond., Ser A*. 316:375-426.

Chen, X., Wu, Y., Cui, W., and Jensen, J. 2006. Review of hydroelasticity theories for global response of marine structures. *Ocean Engineering*, 33(3-4), 439-457.

Chen, X., Wu, Y., Cui, W. and Tang, X., 2003. Non-linear hydroelastic analysis of a moored floating body. *Ocean Eng*. 30 (8), 965–1003.

Dai, J., Ang, K. K., and Zhang, C., 2018. Hydroelastic analysis of modular floating barges for hydrocarbon storage facility: energy and geotechnics. *Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering*. November 1–3. Hanoi, Vietnam,

De Rooij, G.V.P., 2006. A Very Large Floating Container Terminal Feasibility Study – Application Possibilities for the Situation in the Netherlands. Master Thesis. Delft University of Technology.

Diamantoulaki, I., Angelides, D., and Manolis, G., 2008. Performance of pile-restrained flexible floating breakwaters. *Appl Ocean Research*. 30:243–55.

Ding, J., Wu, Y., Zhou, Y., Li, Z., Tian, C., Wang, X., Zhang, Z. and Liu, X., 2019. A direct coupling analysis method of hydroelastic responses of VLFS in complicated ocean geographical environment. *Journal of Hydrodynamics*. 31:582-93.

ElSafty, A., Benmokrane, B., Rizkalla, S., Mohamed, H., and Hassan, M. 2014. Degradation assessment of internal continuous fiber reinforcement in concrete environment. Univ. of North Florida. Materials Research Rep. Contract No. BDK82#977-05. Jacksonville. FL: College of Computing. Engineering and Construction.

Endo, H., 2000. The behaviour of a VLFS and an airplane during takeoff/landing run in wave condition. *Marine Structures*. 13:477–91.

Feng, X., and Bai, W., 2017. Hydrodynamic analysis of marine multibody systems by a nonlinear coupled model. *J Fluid Struct.* 70:72-101.

Ferrerask, J., Peña, E., López, A., and López, F., 2014. Structural performance of a floating breakwater for different mooring line typologies. *J Waterw Port Coastal Ocean Eng*. 140:paper No. 04014007.

Fried, J. 1995. Polymer science and technology: introduction to polymer science. New Jersey: Prentice Hall PTR Inc.

Fu, S., Cui, W., Chen, X., and Wang, C., 2005. Hydroelastic analysis of a nonlinearly connected floating bridge subjected to moving loads. *Marine Structures*. 18:85–107.

Fu, S., Moan, T., Chen, X., and Cui, W., 2007. Hydroelastic Analysis of flexible floating interconnected structures. *Ocean Eng.* 34:1516–31.

Gao, R.P., Tay, Z.Y., Wang, C.M. and Koh, C.G., 2011. Hydroelastic response of very large floating structure with a flexible line connection. *Ocean Engineering*. 38:1957-66.

Gao, R.P., Wang, C.M. and Koh, C.G., 2013. Reducing hydroelastic response of pontoon-type very large floating structures using flexible connector and gill cells. *Engineering Structures*. 52:372-383.

Graybeal, B. A. 2010. Behavior of field-cast ultra-high performance concrete bridge deck connections under cyclic and static structural loading (No. FHWA-HRT-11-023). United States. Federal Highway Administration.

Gu, J., Wu, J., Qi, E., Guan, Y., Yuan, Y., 2015. Time domain calculation of connector loads of a very large floating structure[J]. *Journal of Marine Science and Application*, 14(2): 183–188.

Jiang D, Tan, K.H., Wang, C.M., Ong, K.C.G., Bra, H., Jin, J., and Kim, M., 2018. Analysis and design of floating prestressed concrete structures in shallow waters. *Marine Structures*. 59:301-320.

Jiang, D., Tan, K. H., Dai, J., Ong, K. C. G., and Heng, S., 2019. Structural performance evaluation of innovative prestressed concrete floating fuel storage tanks. *Structural concrete*, 20(1):15-31.

Jørgen, J. J., and Mansour, A. E., 2002. Estimation of the long-term wave-induced bending moment in ships using closed-form expressions. *International Journal of Maritime Engineering*. 144:41–5.

Juncher, J. J. and Terndrup, P. P., 1979. Wave-induced bending moments in ships - a quadratic theory. *Royal Inst Naval Architects Supplementary Papers*. 121:151–65.

Jung K., Lee S., Kim H., Choi Y., and Kang S., 2019. Design and constructuon of concrete floating pier in golden harbor, Incheon. In: *Proceedings of World Conference on Floating Solutions 2019*, vol 41. April 22-23, Singapore.

Kashiwagi, M., 1998a. A B-spline Galerkin scheme for calculating the hydroelastic re- sponse of a very large floating structure in waves. *Journal of Marine Science and Technology*. 3:37–49.

Kashiwagi, M., 1998b. A hierarchical interaction theory for wave forces on a large number of elementary bodies of a semi-sub type VLFS. *Proceedings of 14th ocean engineering symposium*. 425–31.

Kashiwagi, M., 2000. A time-domain mode-expansion method for calculating transient elastic responses of a pontoon-type VLFS. *Journal of Marine Science and Technology*. 5:89–100.

Kashiwagi, M., 2004. Transient responses of a VLFS during landing and take-off of an airplane. *Journal of Marine Science and Technology*. 9:14-23.

Khabakhpasheva, T., and Korobkin, A., 2002. Hydroelastic behaviour of compound floating plate in waves. *Journal of Engineering Mathematics*. 44:21–40.

Kim, B., Hong, S., Kyoung, J. and Cho, S., 2007. Evaluation of bending moments and shear forces at unit connections of very large floating structures using hydroelastic and rigid body analyses. *Ocean Eng*. 34.

Kim, Y., and Kim, K., 2009. Analysis of hydroelasticity of floating shiplike structure in time domain using a fully coupled hybrid BEM-FEM. *J Ship Res.* 50:31–47.

Koekoek, M.J., 2006. Connecting Modular Floating Structures: A General Survey and Structural Design of a Modular Floating Pavilion. Master Thesis. Delft University of Technology.

Lakshmynarayanana, P., and Temarel, P., 2019. Application of CFD and FEA coupling to predict dynamic behaviour of a flexible barge in regular head waves. *Marine Structures*. 65:308-25.

Lee, C., and Newman, J.N., 2000. An assessment of hydroelasticity for very large hinged vessels. *J Fluids Struct*. 14:957–70.

Lee, K. H., and Lee, P. S., 2016. Nonlinear hydrostatic analysis of flexible floating structures. *Appl. Ocean Res.*; 59, 165–182.

Lee, S., Takaki, M. and Iwano, M., 2003. Estimation of the radiation forces on submerged-plate oscillating near a free surface by composite grid method. *Trans West-Jpn Soc Nav Arch*. 105:113–22.

Lei H. H., 2007. Securing of marine platforms in rough sea. *Recent Patents on Engineering*. 1:103-112.

Li, J., Wu, Z., Shi, C., Yuan, Q., and Zhang, Z. 2020. Durability of ultrahigh performance concrete–

A review. *Construction and Building Materials*, 255, 119296.

Liu, C., 2014. Research on Structural Response of Multi-Module Flexible Connectors for Very Large Floating Structures. Mater Thesis, China Ship Scientific Research Center, Wuxi, China.

Liu, C., Qi, E., Lu, Y., 2014. Dynamic response of connectors of Very Large Floating Structures under shallow draft. *Journal of Ship Mechanics*. 18(05):581-590. (in Chinese)

Liu, X., and Sakai, S., 2002. Time domain analysis on the dynamic response of a flexible floating structure to waves. *Journal of Engineering Mechanics*. 128:48–56.

Lotsberg, I. 2016. Fatigue design of marine structures. Cambridge University Press: UK.Loukogeorgaki, E., Michailides, C. and Angelides, D., 2012. Hydroelastic analysis of a flexible mat-shaped floating breakwater under oblique wave action. *J Fluid Struct*. 31:103-24.

Loukogeorgaki, E., Yagci, O. and Kabdasli, M., 2014. 3D Experimental investigation of the structural response and the effectiveness of a moored floating breakwater with flexibly connected modules. *Coastal Engineering*. 91:164-180.

Martinelli, L., Zanuttigh, B., and Ruol, P., 2008. Wave basin experiments on floating breakwaters with different layouts. *Appl Ocean Res*. 30:199–207.

Mcallister K., 1997. Mobile offshore bases—An overview of recent research. *Journal of Marine Sciences and Technology*. 2:173-181.

Michailides, C., Loukogeorgaki, E., and Angelides, D., 2013. Response analysis and optimum configuration of a modular floating structure with flexible connectors. *Appl Ocean Res.* 43:112–30.

Namba, Y., and Ohkusu, M., 1999. Hydroelastic behavior of floating artificial islands in waves. *International Journal of Offshore and Polar Engineering*. 9:39–47.

Nematbakhsh, A., Gao, Z. and Moan, T., 2017. Benchmarking of a computational fluid dynamics-based numerical wave tank for studying wave load effects on fixed and floating offshore structures. *J Offshore Mech Arctic Eng.* 139:031301.

Newman, J.N., 1994. Wave effects on deformable bodies. *Appl Ocean Res*. 1994: 47–59.

Newman, J.N., 1997. Wave effects on hinged bodies. Part II –hinge loads.

Nguyen, H.P., Wang, C.M., Flocard, F., and Pedroso, D.M., 2019. Extracting energy while reducing hydroelastic responses of VLFS using a modular raft WEC-type attachment. *Appl. Ocean Res.* 84, 302–316

Ohkusu, M., and Namba, Y., 2004. Hydroelastic analysis of a large floating structure. *J Fluid Struct.*

19:543-55.

Ohmatsu, S. 2005. Overview: Research on wave loading and responses of VLFS. *Marine Structures*, 18(2), 149-168.

Pantelides, C., Reaveley, L., McMullin, P. 2003. Design of CFRP Composite Connector for Precast Concrete Elements. *Journal of Reinforced Plastics and Composites*. 22(15):1335-1351.

Peña, E., Ferreras, J., and Sanchez-Tembleque, F., 2011. Experimental study on wave transmission coefficient, mooring lines and module connector forces with different designs of floating breakwaters. *Ocean Eng*. 38:1150–60.

Qi, E., Liu, C., Xia, J., Lu, Y., Li, Z., Yue, Y., 2015. Experimental study of functional simulation for flexible connectors of very large floating structure. *Journal of Ship Mechanics*. 19(10):1245-1254.

Qi, E., Song, H., Li, Z., Zhang, H., Xia, J., Zhu, Y., 2017. S Model test of fatigue strength of a flexible connector of very large floating structures. *Journal of Ship Mechanics*. 21(11):1374-1382.

Qi, E., Song, H., Lu, Y., Li, Z., Xia, J., 2017. Study on dynamic response of flexible connectors of very large floating structures. *Proceedings of the Conference to Mark the 20th Anniversary of Journal of Ship Mechanics*. 9:218-226 (in Chinese).

Rahman M. A., and McQuaker, T. 2016. “Application of ultra high performance concrete in expediting the replacement and rehabilitation of highway bridges.” Proc., First Int. Interactive Symp. on UHPC, Iowa State Univ., Des Moines, Iowa.

Ramsamooj, D. V. and Shugar, T. A., 2001. Prediction of fracture-based fatigue life of connectors for the mobile offshore base. *Marine Structures*,2001,14(1)： 197-214.

Ramsamooj, D. V. and Shugar, T. A., 2002. Reliability analysis of fatigue life of the connectors-the US mobile offshore base. *Marine Structures*. 15:233–250.

Ren, N., Zhang, C., Magee, A.R., Hellan, Ø., Dai, J., and Ang, K.K., 2019. Hydrodynamic analysis of a modular multi-purpose floating structure system with different outermost connector types. *Ocean Eng.* 176, 158–168.

Riggs, H.R., and Ertekin, R.C., 1993. Approximate methods for dynamic response of multi-module floating structures. *Marine Structures*. 6: 117-141.

Riggs H.R., Ertekin, R.C., and Mills, T., 1999. Impact of stiffness on the response of a multimodule mobile offshore base. *International Journal of Offshore and Polar Engineering*. 9:126-33.

Riggs, H., Ertekin, R., and Mills, T., 2000. A comparative study of RMFC and FEA models for the wave-induced response of a MOB. *Marine Structures*. 13:217–32.

Riyansyah, M., Wang, C.M. and Choo, Y.S., 2010. Connection design for two-floating beam system for minimum hydroelastic response. Marine Structures. 23(1), 67-87.

Rognaas, G, Xu, J., Lindseth, S., and Rosendahl, F., 2001. Mobile offshore base concepts concrete hull and steel topsides. *Marine Structures*. 14:5-23.

Sen, R., Shahawy, M., Rosas, J., Sukumar, S., 1998a. Durability of aramid pretensioned elements in a marine environment. *ACI Struct J*. 95(5):578–87.

Sen, R., Shahawy, M., Rosas, J., Sukumar, S., Rosas, J. , 1998b. Durability of carbon pretensioned elements in a marine environment. *ACI Struct J*. 95(6):716–24.

Senjanovic, I., Catipovic, I., and Tomasevic, S., 2008. Coupled horizontal and torsional vibrations of a flexible barge. *Engineering Structures*. 30:93–109.

Senjanovic, I., Malenica, S., and Tomasevic, S., 2008a. Investigation of ship hydroelasticity. *Ocean Engineering*. 35:523–35.

Senjanovic, I., Tomic, M., and Tomasevic, S., 2008b. An explicit formulation for restoring stiffness and its performance in ship hydroelasticity. *Ocean Engineering*. 35:1322–38.

Shi, C., Wu, Z., Xiao, J., Wang, D., Huang, Z., and Fang, Z. 2015. A review on ultrahigh performance concrete: part I. Raw materials and mixture design, *Constr. Build. Mater*. 101:741–751.

Shi, Q., Xu, D., and Zhang, H., 2018. Design of a flexible-base hinged connector for very large floating structures. *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*.

Suzuki, H., 2005. Overview of Megafloat: concept, design criteria, analysis, and design. *Mar. Struct.* 18, 111–132.

Taylor, R., 2007. Wet hydroelastic analysis of plates and some approximations. *Journal of Engineering Mathematics*. 58:267–78.

Teng, B.. Gou, Y., Wang, G. and Cao, G., 2014. Motion response of hinged multiple floating bodies on local seabed. *Proceedings of the Twenty-Fourth International Offshore and Polar Engineering Conference (ISOPE 2014)*. Busan, South Korea; 591-8.

Wang, C., Fu, S., and Cui, W. 2009. Hydroelasticity based fatigue assessment of the connector for a ribbon bridge subjected to a moving load. *Marine structures*, 22(2), 246-260.

Wang, C.M., Riyansyah, M., and Choo, Y. S., 2009. Reducing hydroelastic response of interconnected floating beams using semi-rigid connections. *Proceedings of the ASME 28th International Conference on Offshore Mechanics and Arctic Engineering*, May 31 - June 5, Honolulu, Hawaii, USA, OMAE2009-79692.

Wang, C.M., and Tay, Z.Y., 2011. Very large floating structures: applications, research and development. *Procedia Engineering*. 14:62-72.

Wang C.M. and Wang, B.T., 2015. Large Floating Structures: Technological Advances. Singapore: Springer Singapore.

Wang, D., Shi, C., Wu, Z., Xiao, J., Huang, Z., and Fang, Z. 2015. A review on ultrahigh performance concrete: part II. Hydration, microstructure and properties, *Constr. Build. Mater.* 96: 368–377.

Wang, D.Y., Riggs, H.R., Ertekin, R.C., 1991. Three-dimensional hydroelastic response of a very large floating structure. *International Journal of Offshore and Polar Engineering*. 1:307–16.

Wang, P., Yu, L., Li, R., 2002. A time sequence analysis method for predicting connector loads in a semi-submersible very large floating structure. *China Ocean Engineering*. 20(3):9-13. (in Chinese)

Watanabe, E., Utsunomiya, T., and Tanigaki, S., 1998. A transient response analysis of a very large floating structure by finite element method. *JSCE Structural Engrg/Earthquake Engrg*. 15:155–63.

Watanabe E, Utsunomiya, T., and Wang, C. M., 2004. Hydroelastic analysis of pontoon-type VLFS: a literature survey. *Engineering structures*. 26:245-56.

Wilkins D., 2002. Interlocking System, Apparatus and method for connecting modules." US patent no. 6470820.

Wei, W., Fu, S., Moan, T., Liu, Z., and Deng, S., 2017. A discrete-modules-based frequency domain hydroelasticity method for floating structures in inhomogeneous sea conditions. *Journal of Fluids and Structures*, 74:321-339.

Wei, W., Fu, S., Moan, T., Song, C., and Ren, T., 2018. A time-domain method for hydroelasticity of very large floating structures in inhomogeneous sea conditions. *Marine Structures*, 57:180-192.

Wu, C., Watanabe, E., and Utsunomiya, T., 1995. An eigenfunction expansion matching method for analysis wave-induced response of a large floating plate. *Applied Ocean Research*. 17:301–10.

Wu, Y., and Cui, W., 2009. Advances in the three dimensional hydroelasticity of ships. *Proceedings of the Institution of Mechanical Engineers, Part M: J Engng Maritime Environment*. 223:331-48.

Wu, Y., Maeda, H., and Kinoshita T., 1997. The second order hydrodynamic actions on flexible body. Departmental Bulletin Paper, Institute of Industrial Science, the University of Tokyo. 49(4):190-201.

Xia, D., Kim, J., and Cengiz Ertekin, R., 2000. Review on Conceptual Designs and Key Technologies of Very Large Floating Structures. *Journal of Ship Mechanics*. 24(6):135-148.

Xia, S., Xu, D., Zhang, H., Qi, E., Hu, J., and Wu, Y., 2016. On retaining a multi-module floating structure in an amplitude death state. *Ocean Engineering*. 121:134-142.

Xie, Z., Gu, X., Ding, J., Zhao, N., and Hang, G., 2020. On retaining a multi-module floating structure in an amplitude death state. *Ocean Engineering*. 121:134-142.

Xu, D., Zhang, H., Lu, C., Qi, E., Hu, J. and Wu, Y., 2014. On study of nonlinear network dynamics of flexibly connected multi-module very large floating structures. *Vulnerability, Uncertainty, Risk*. 1805–14.

Yoon, D.G. and Boldbaatar, T., 2013. A Study on the connector of floating platform based on concrete structures. *Journal of Korean Society of Marine Environment and Safety*. 19:37–44.

Yoon, J., Cho, S., Jiwinangun, R. G., and Lee, P., 2014. Hydroelastic analysis of floating plates with multiple hinge connections in regular waves. *Marine Structures*. 36:65-87.

Yu, J., Dong, W., Dai, Y., 2006a. The Application of RMFC Model in the Three-Dimensional Motion Response Calculation of New Concatenation Type Maritime Quay of Landing Stage. *Port Engineering Technology*. 4: 1-4. (in Chinese)

Yu, J., Su, C., 2006b. Research on motion ability calculation method of offshore moving trestle. *China Harbour Engineering*. 146(6): 14-17. (in Chinese)

Yu, L., Ding, W., Li, R., 2004. Effect of the multiple modules interaction on MOB connector loads. *China Ocean Engineering*. 37(8): 1159-1163. (in Chinese)

Yu, L., Li, R., Lu, Y., 2003. Dynamic Characteristics of Mobile Offshore Base Connectors. *Journal of Shanghai Jiaotong University*. 37(8): 1159-1163. (in Chinese)

Yuan, J., and Graybeal, B. 2016. Full-scale testing of shear key details for precast concrete box-beam bridges. *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000906, 04016043.

Zhao, C., Hao, X., Liang, R., and Lu, J., 2015. Influence of hinged conditions on the hydroelastic response of compound floating structures. *Ocean Eng*. 101:12-24.

Zhang, H., Qi, E., Song, H., Li, Z., Xia, J., 2019. Study on mechanical property of connector with flexible sandwich of very large floating structures. *Journal of Ship Mechanics*. 23(02):200-210.

Zhang, H.C., Xu, D.L., Ding, R., Zhao, H., Lu, Y., and Wu, Y.S., 2019. Embedded Power Take-Off in hinged modularized floating platform for wave energy harvesting and pitch motion suppression. *Renew. Energy* 1176–1188.

Zhao, N., Gu, X., Qi, E., Li, S., Tang, M., 2018. Theoretical and experimental study on the ultimate strength of the VLFS connector foundation support reinforcing area structure under complex loads. *Journal of Ship Mechanics*. 22(07):857-864.

Zhao, H., Xu, D., Zhang, H., Xia, S., Shi, Q., Ding, R., and Wu, Y., 2019. An optimization method for stiffness configuration of flexible connectors for multi-modular floating systems. *Ocean Engineering*. 181:134–44.

Table 1. Results of Combined Compliant Connectors on Sides of Floating Module (De Rooij, 2006)

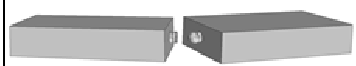
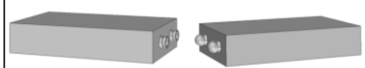
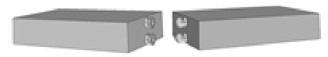
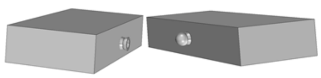
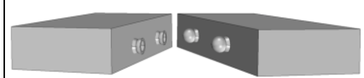
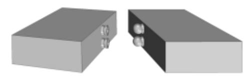
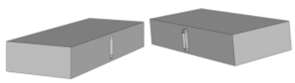
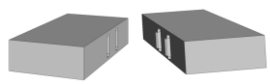
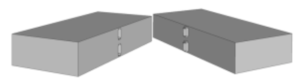
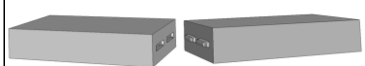
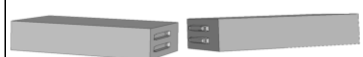
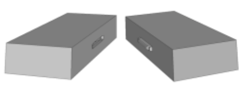
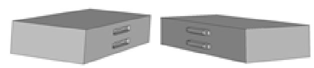
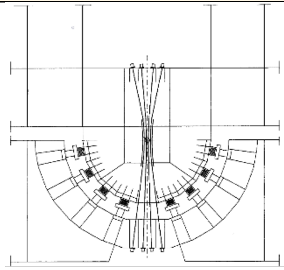
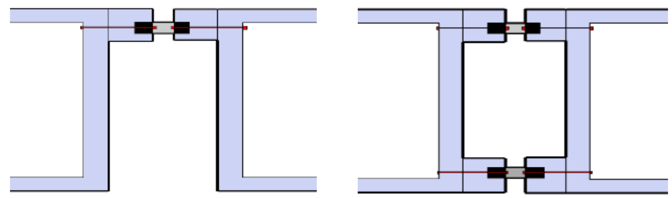
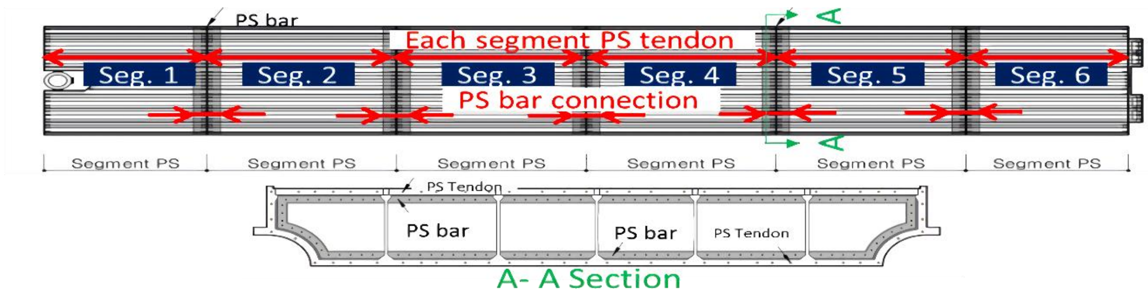
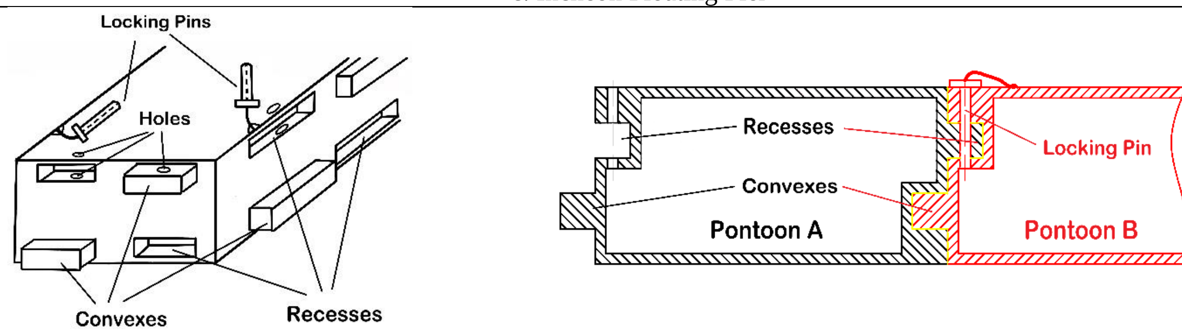
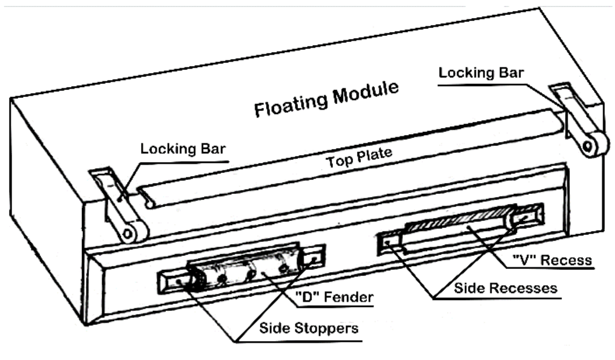
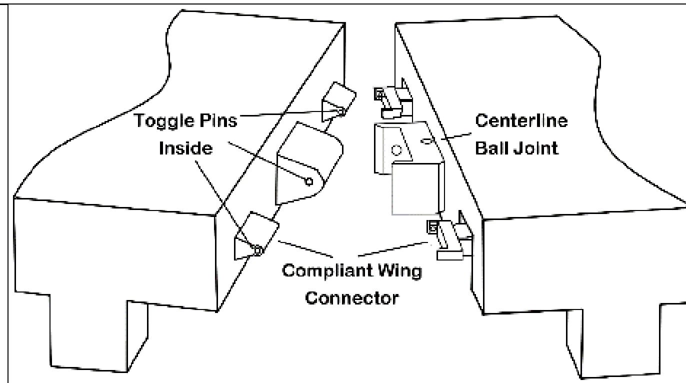
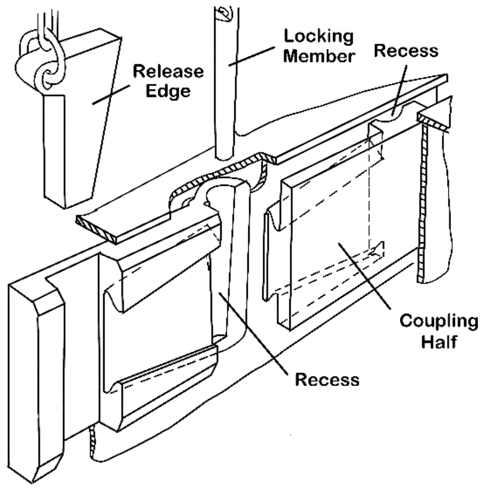
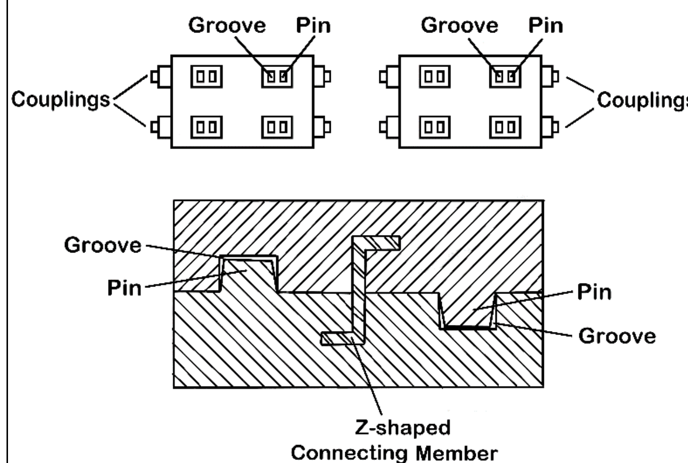
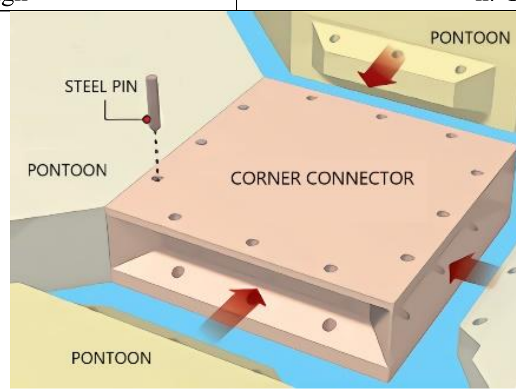
Type & Direction of connector		Extra restrained DOF.	
	Allowed DOF by 1 connector	2 hinges, (hor.) next to each other	2 hinges, (vert.) above each other
Centre point short face	all rotations 	roll, yaw 	pitch 
Centre point long face	all rotations 	pitch, yaw 	roll 
Vertical element long face	yaw 	yaw 	- 
Horizontal element short face	pitch 	yaw 	pitch 
Horizontal element long face	roll 	yaw 	roll 

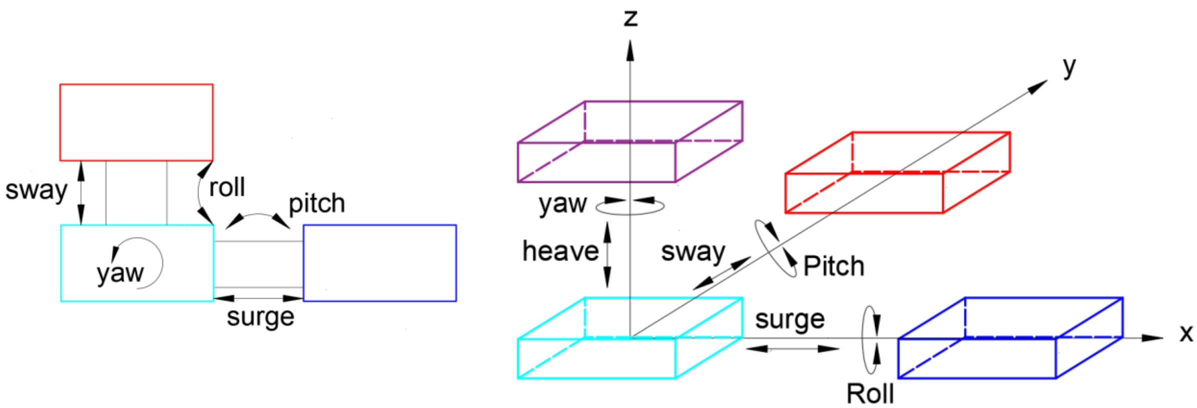
Table 2. Positive and Negative Aspects of Rigid and Flexible Connector Systems

Type	Positive Aspects	Negative Aspects
Rigid Connector System	• Small or no motions • Easy internal transport of containers • Complies with crane track requirements	• Large connection forces • Complex connection configuration • Difficult to decouple the connectors
Flexible Connector System	• Low connection forces • Easy decoupling process	• Large motion amplitude • Complex internal transport • Flexible platform deck

Table 3. Rigid Connector Systems Developed with Different Design Principles

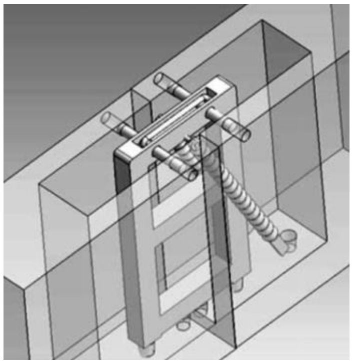
Principles	Typical Examples	Advantages	Disadvantages
Cable “Tensioning”	 a. Rognaas’ Design  b. Halim’s Design  c. Incheon Floating Pier	1. Well distributed connection forces 2. Low cost 3. Adjustable connection stiffness	1. Weakness in shear aspects from heave motions 2. Vulnerable against corrosion 3. Difficult to disassemble
Hinge “Clicking”	 d. Armin’s Design	1. Well transferred forces	1. Relatively expensive 2. Easily damaged 3. Difficult for inspection or maintenance 4. Expensive to disassemble

	 e. Han's Connector	 f. McDermotts MOB Connection		
Tooth "Anchoring"	 g. Bargeco's Design	 h. Gardner's Design	1. Bear high loads 2. Easy to disassemble 3. Not vulnerable	1. Accurate installation job needed 2. Margins required during coupling
	 i. Marina Bay Float			

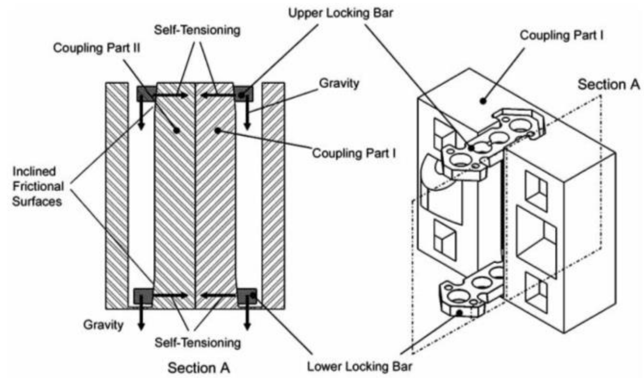


Top View Side View

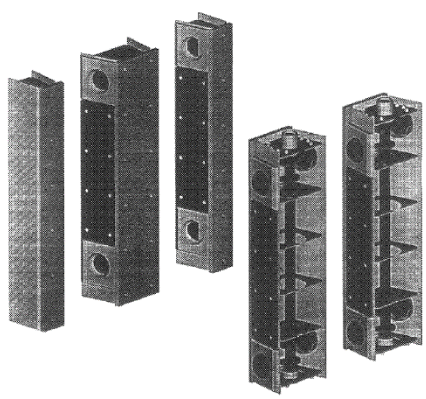
Figure 1. Relative Motions of Connected Floating Modules.



(a) Au-Yeong's Design (Yoon and Boldbaatar, 2013)

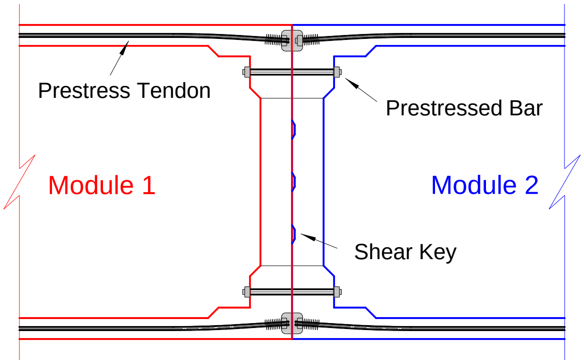


(b) Han's Frictional Locking Connector (Yoon and Boldbaatar, 2013)

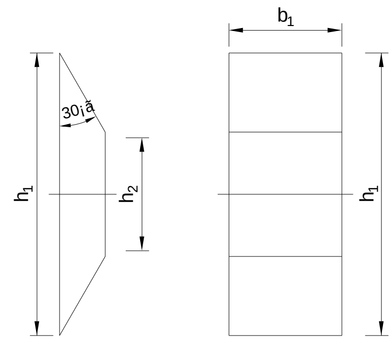


(c) Wilkins's Connector System (Wilkins, 2002)

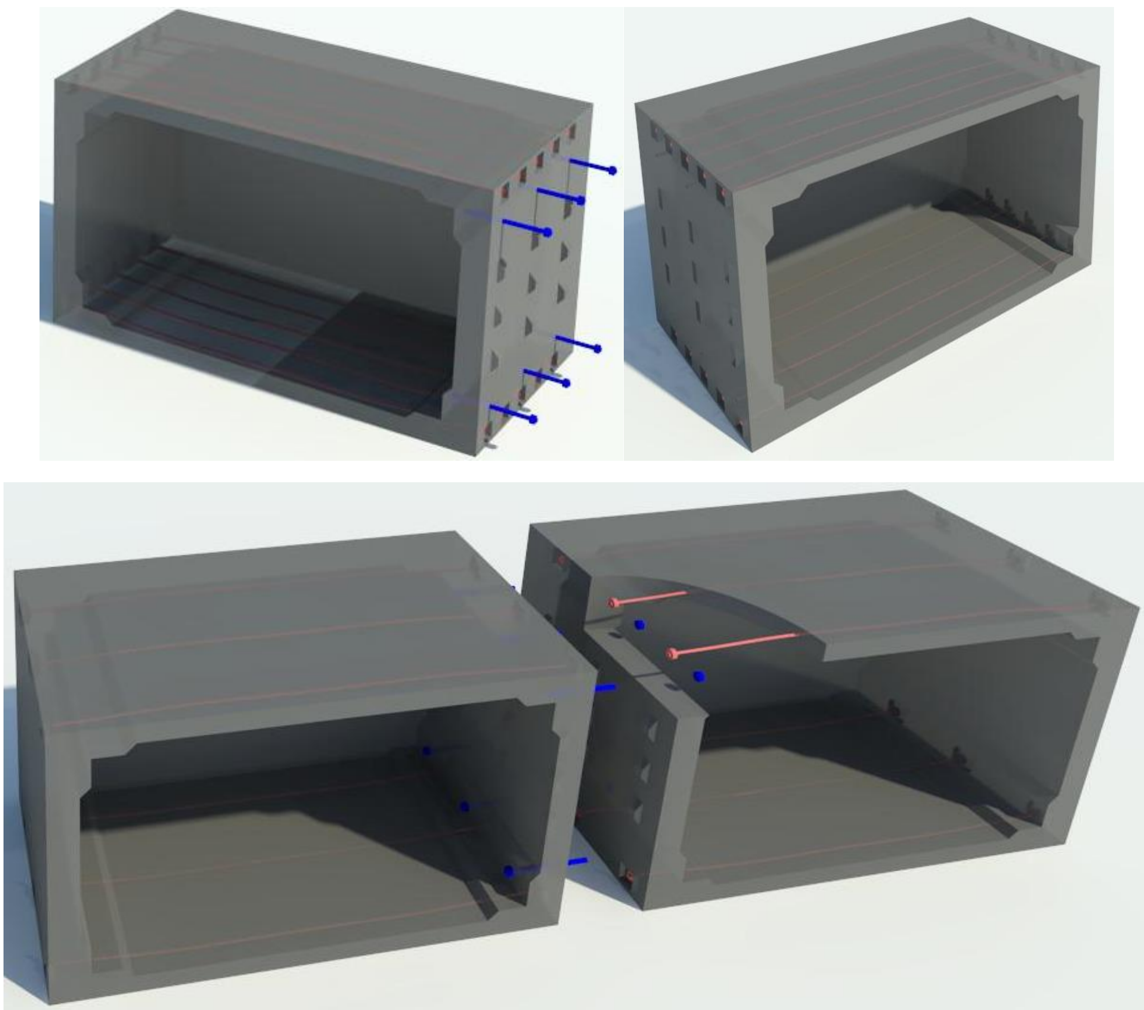
Figure 2. Connector Systems Using Bolts or Bars.



(a) Sectional View

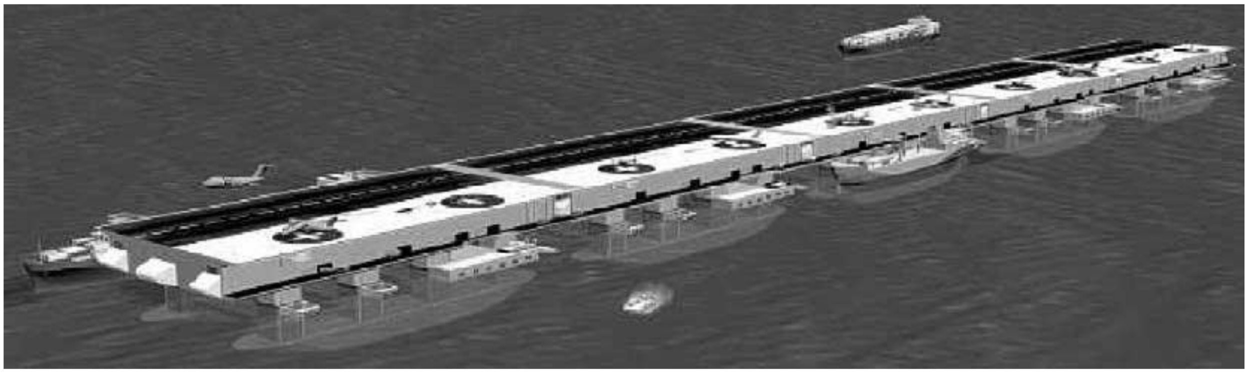


(b) Shear Key

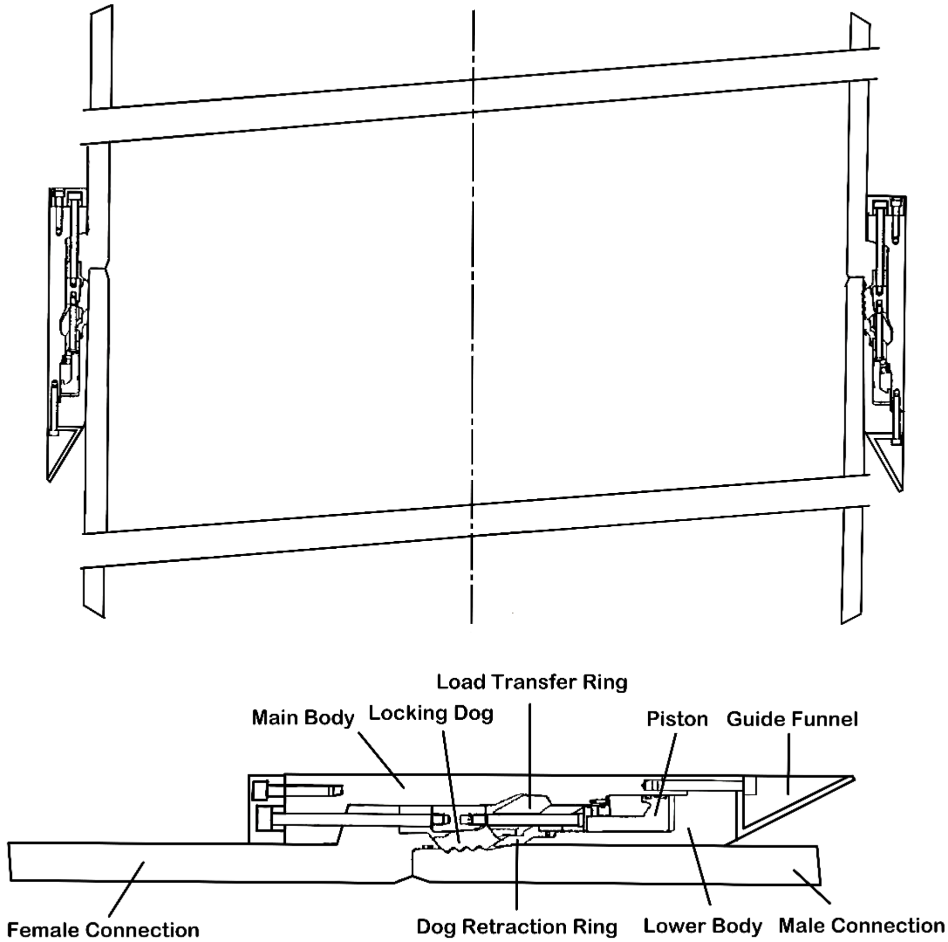


(c) Three-dimensional View of Inter-connected Floating Module

Figure 3. Prestressed Concrete Shear Key Connection.

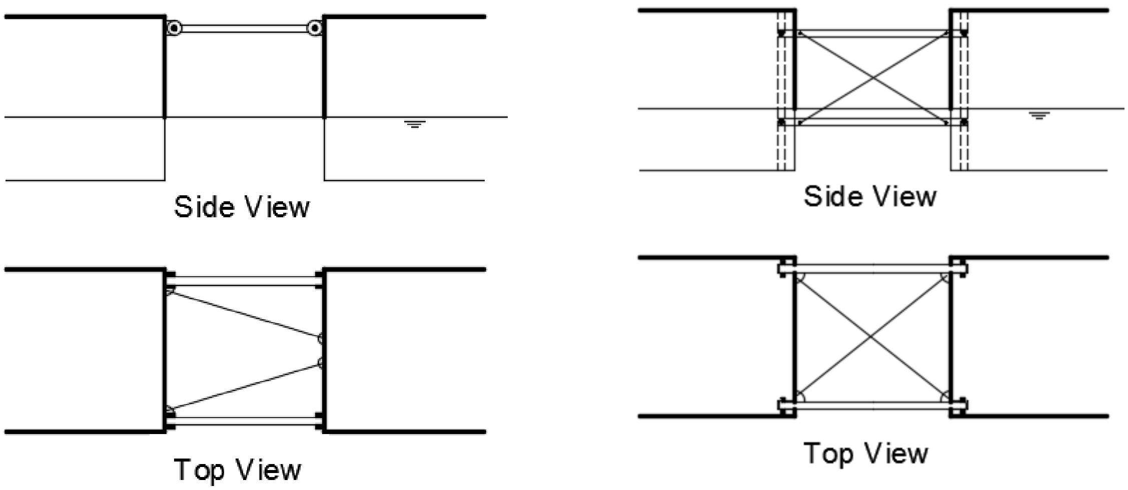


(a) Rigidly connected semi-submersible modules of MOB



(b) ABB Vetco Grey latching system for connector

Figure 4. Rigid Connector System for MOB Proposed by Brown and Root (Ramsamooj and Shugar, 2002).



(a) “Rotation Allowing” Connection (b) “Rotation Restricting” Connection

Figure 5. Vertical-free Connector Systems (Koekoek, 2006).

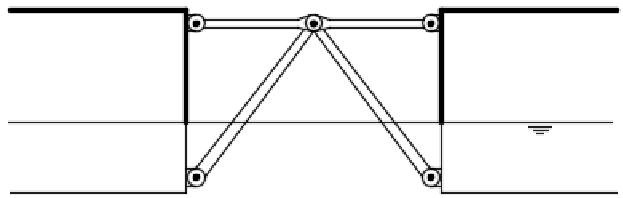
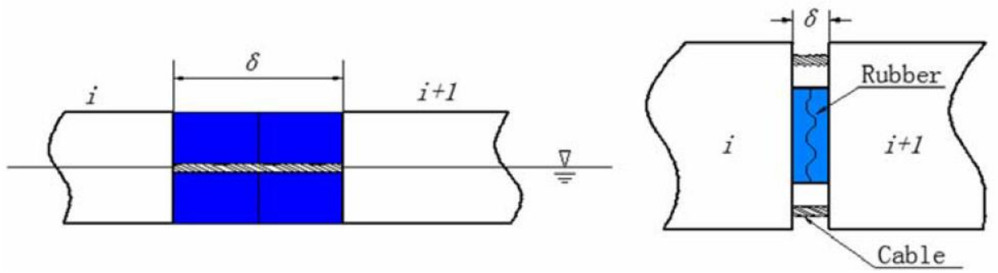


Figure 6. Hinge Connector Systems (Koekoek, 2006).



(a) Side View (b) Plan View

Figure 7. Rubber-Cable Connector System (Xu et al. 2014).

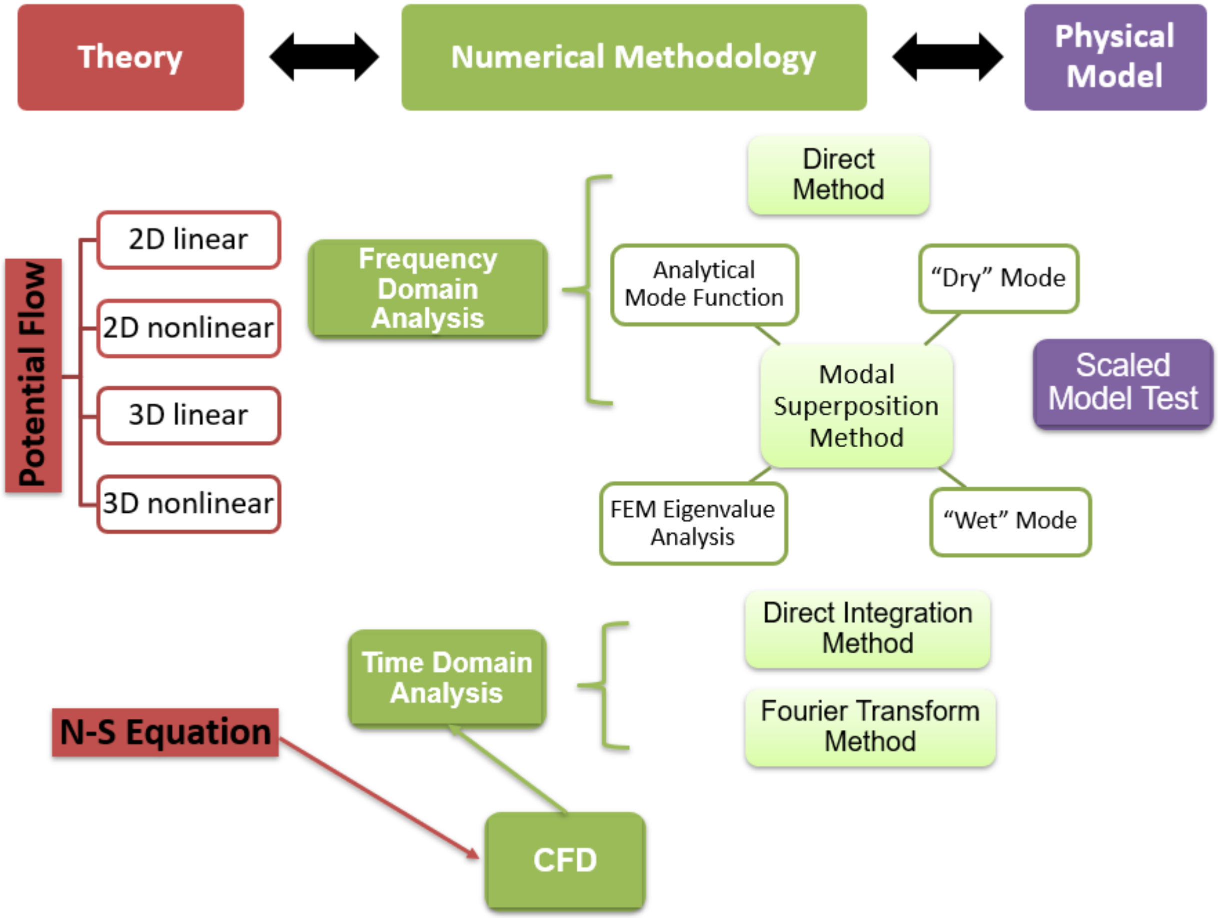
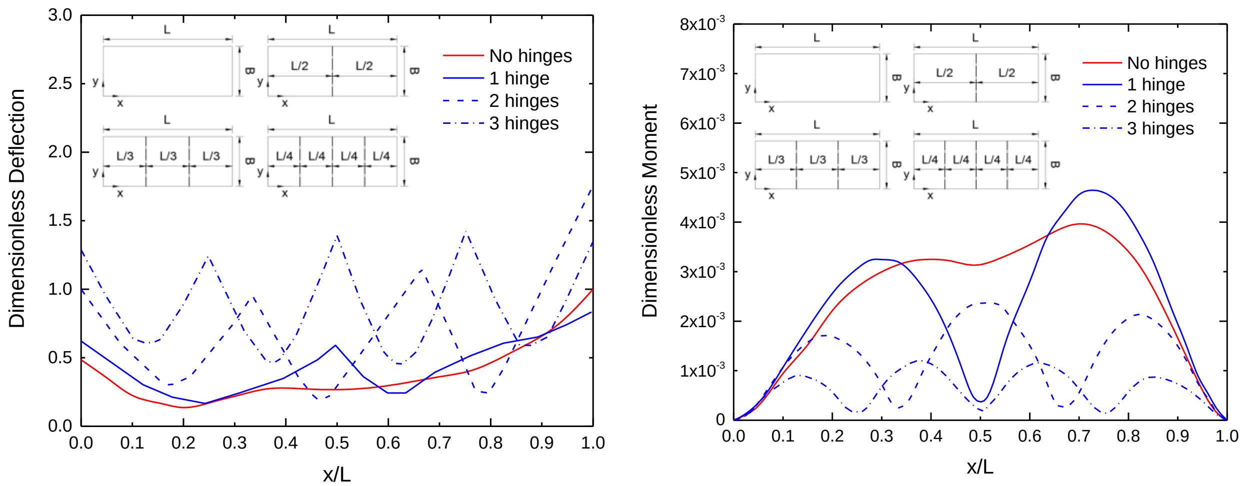


Figure 8. System of Numerical Methods for Hydroelastic Analysis.



(a) RAOs of dimensionless vertical deflection (b) RAOs of dimensionless bending moment

Note: Response amplitude operators (RAOs) of the dimensionless bending moment and deflection are defined as follows: $\bar{M}_{yy} = \left|M_{yy}\right| / \rho_w g L^2$ and $\bar{u}_3 = \left|u_3\right| / a$, where M_{yy} is the RAO of the bending moment per unit width, L is the length of floating plate, u_3 is the vertical deflection and a is the distance between two adjacent reflective markers (a = 0.42 m in Yoon et al. (2014)).

Figure 9. Hydroelastic Responses of Floating Plates with Multiple Hinge Connections in Head Sea (Adapted from Yoon et al. (2014)).

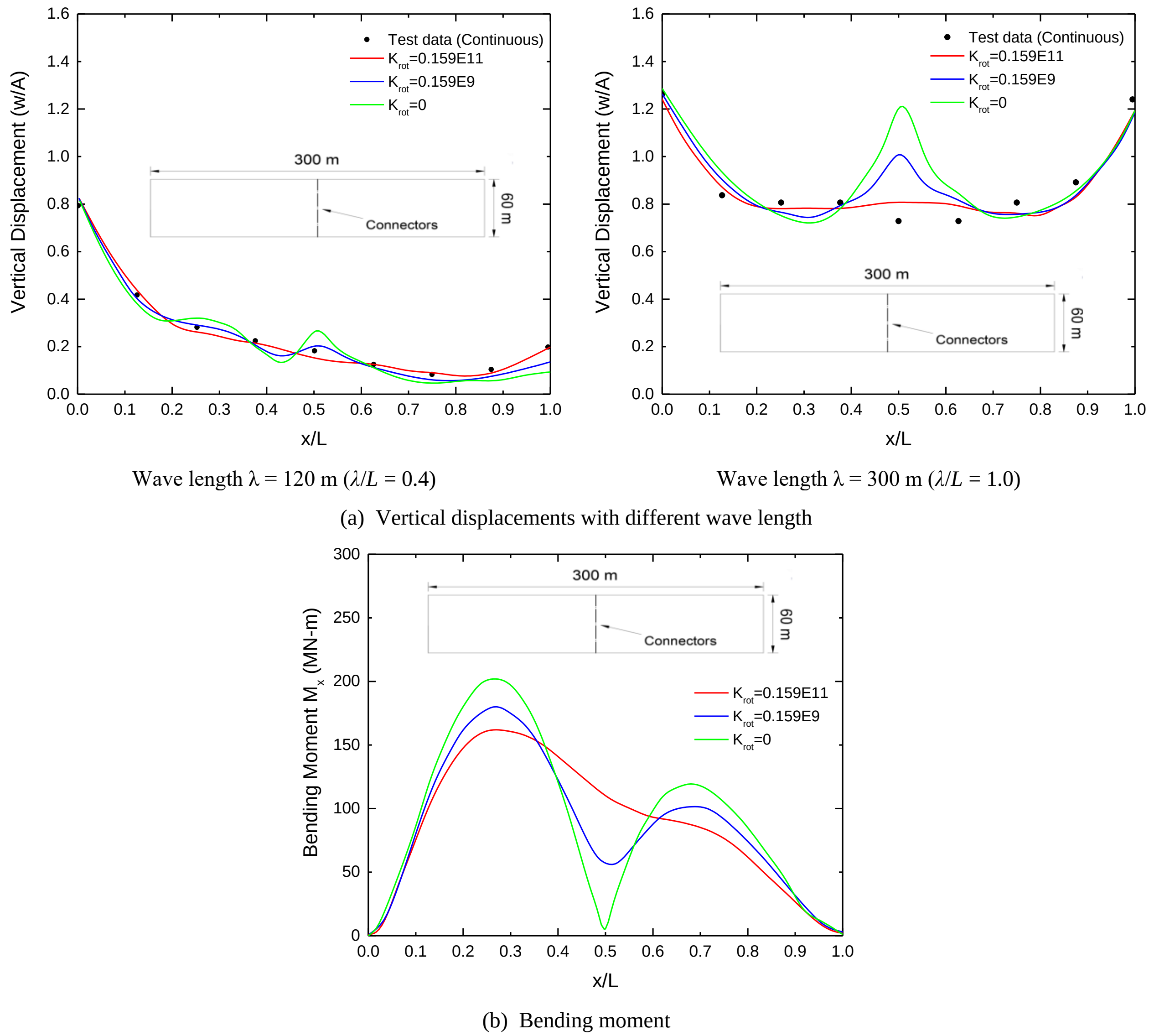


Figure 10. Effects of Rotational Stiffness on Hydroelastic Response of Floating Modules Interconnected with Flexible Connectors with Varying Rotational Stiffness (Adapted from Fu et al. (2007)).

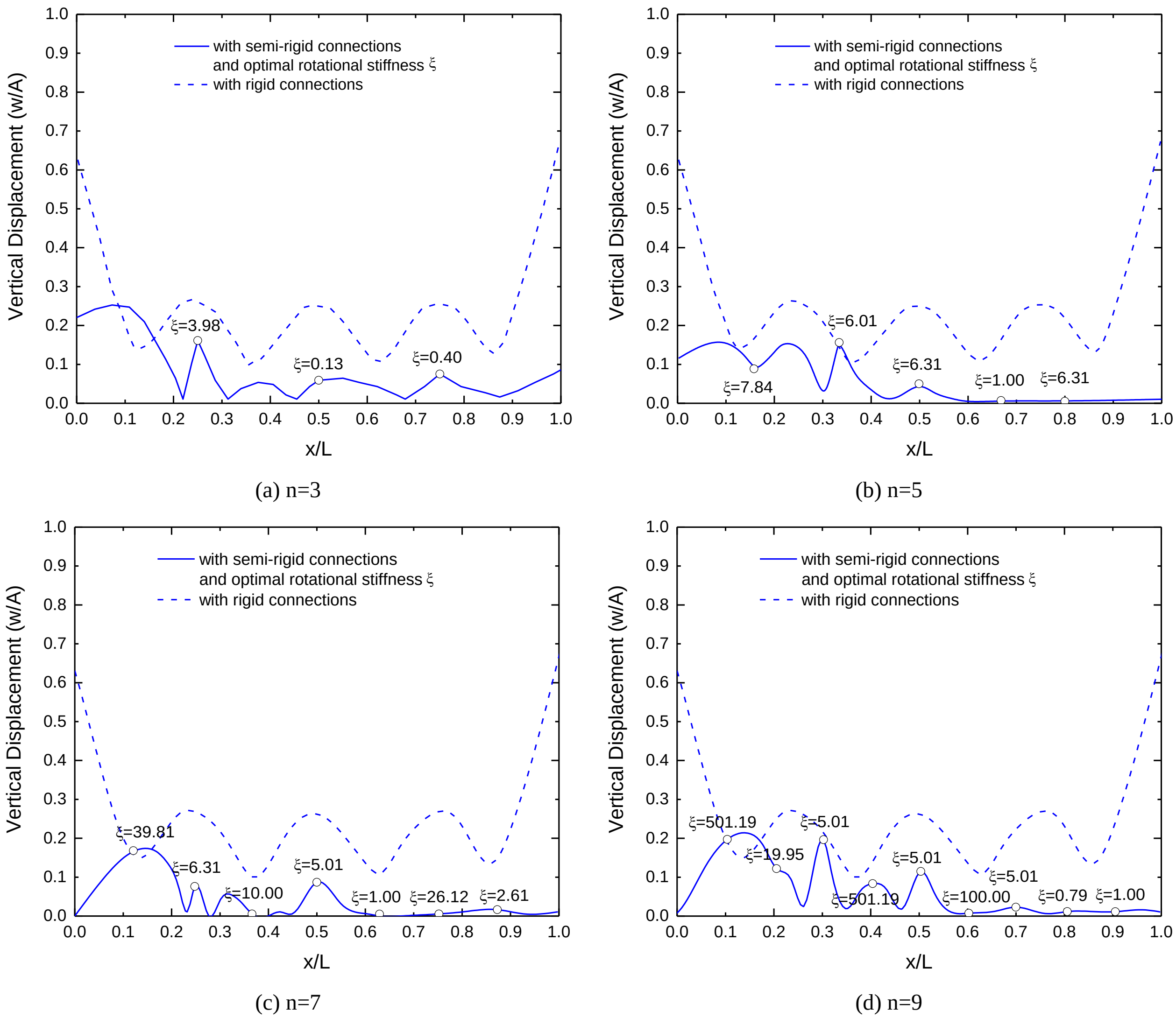
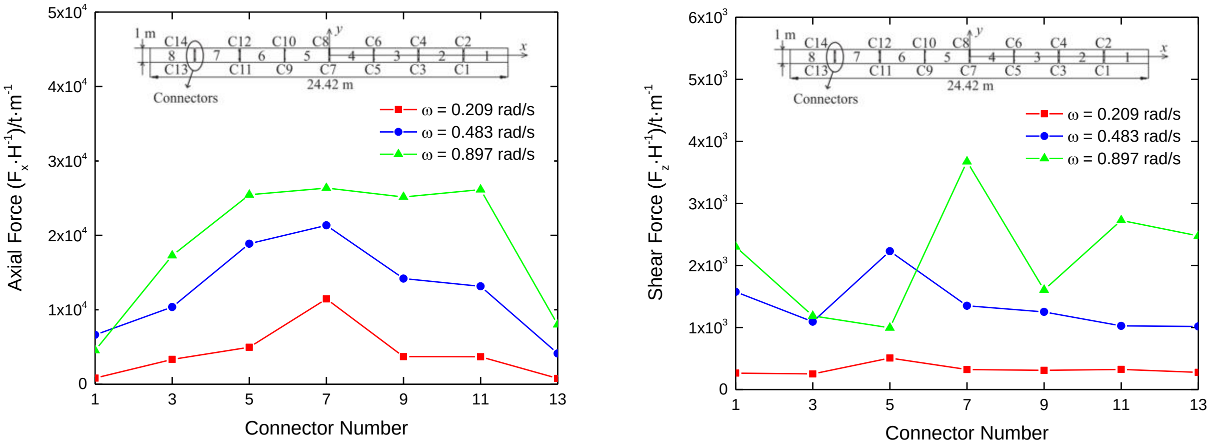
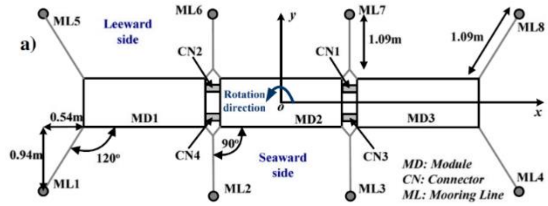


Figure 11. Hydroelastic Responses of Floating Beam with Optimum Locations and Optimum Rational Stiffness for (a) n=3, (b) n =5, (c) n=7, and (d) n=9. Structural Length *L* = 300 m, Water Depth *H* = 20 m (Adapted from Wang et al. (2009)).

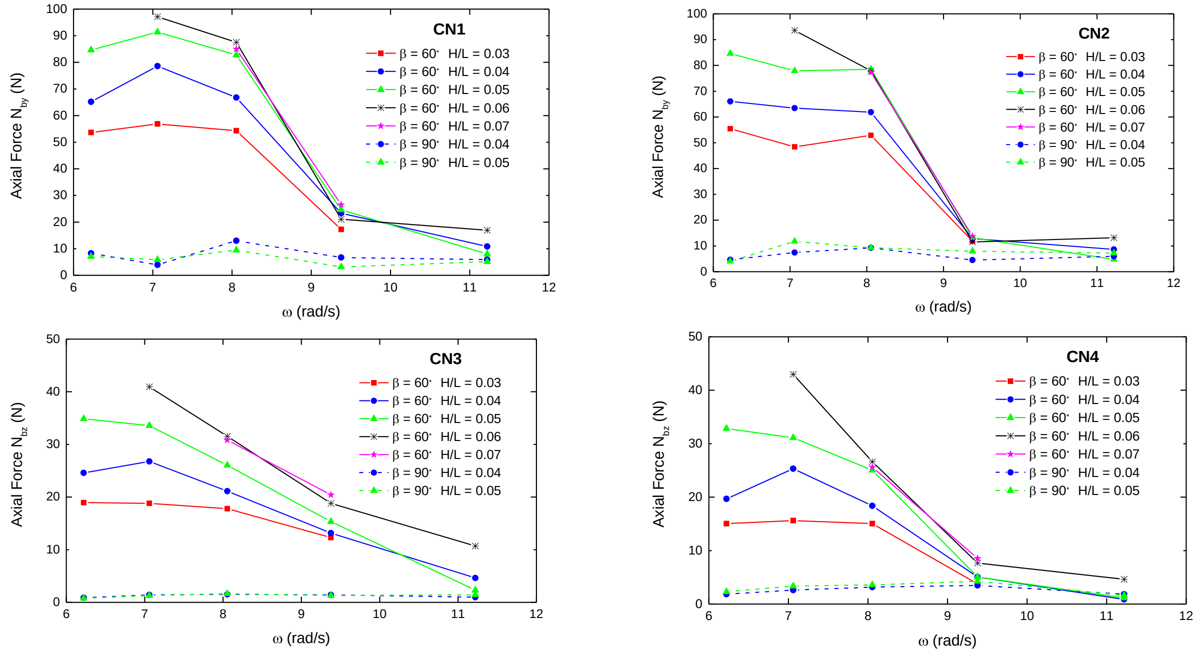


(a) Axial Force F_x (b) Shear Force F_z

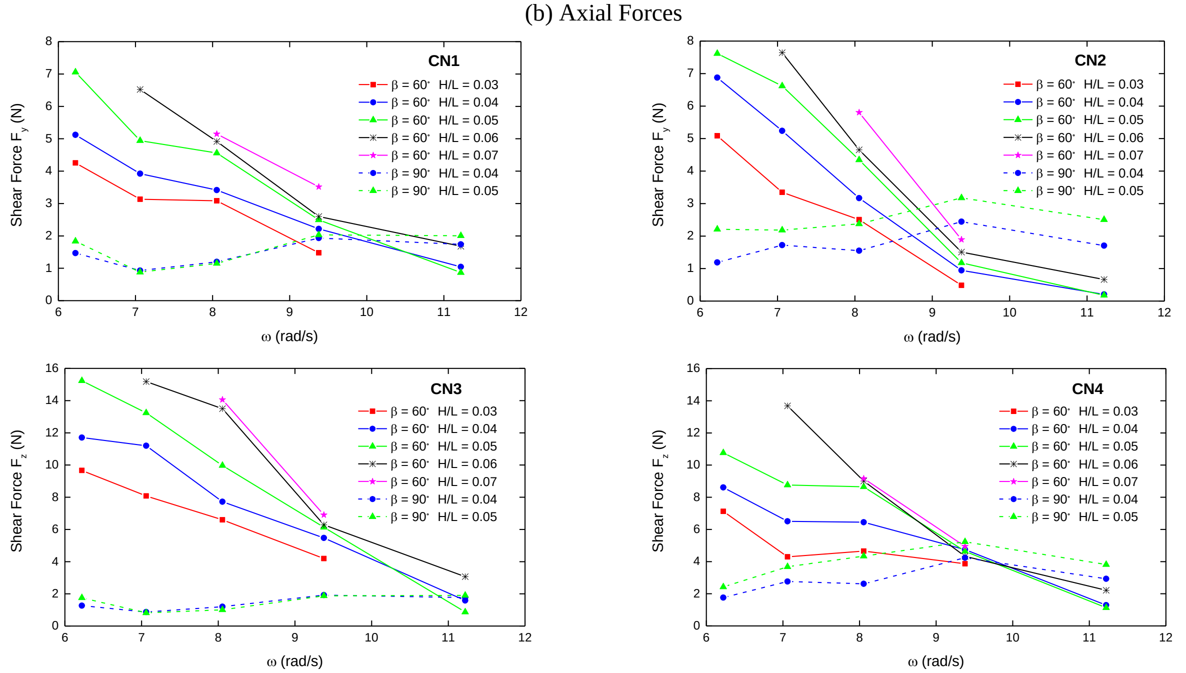
Figure 12. Variation of Connecting Forces along Length of Longish VLFS from C1 to C13 (Adapted from Ding et al. (2019)).



(a) Interconnected Floating Modules



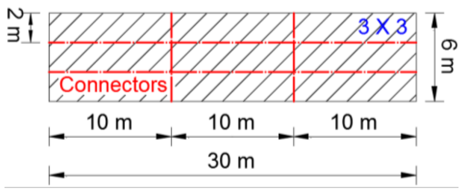
(b) Axial Forces



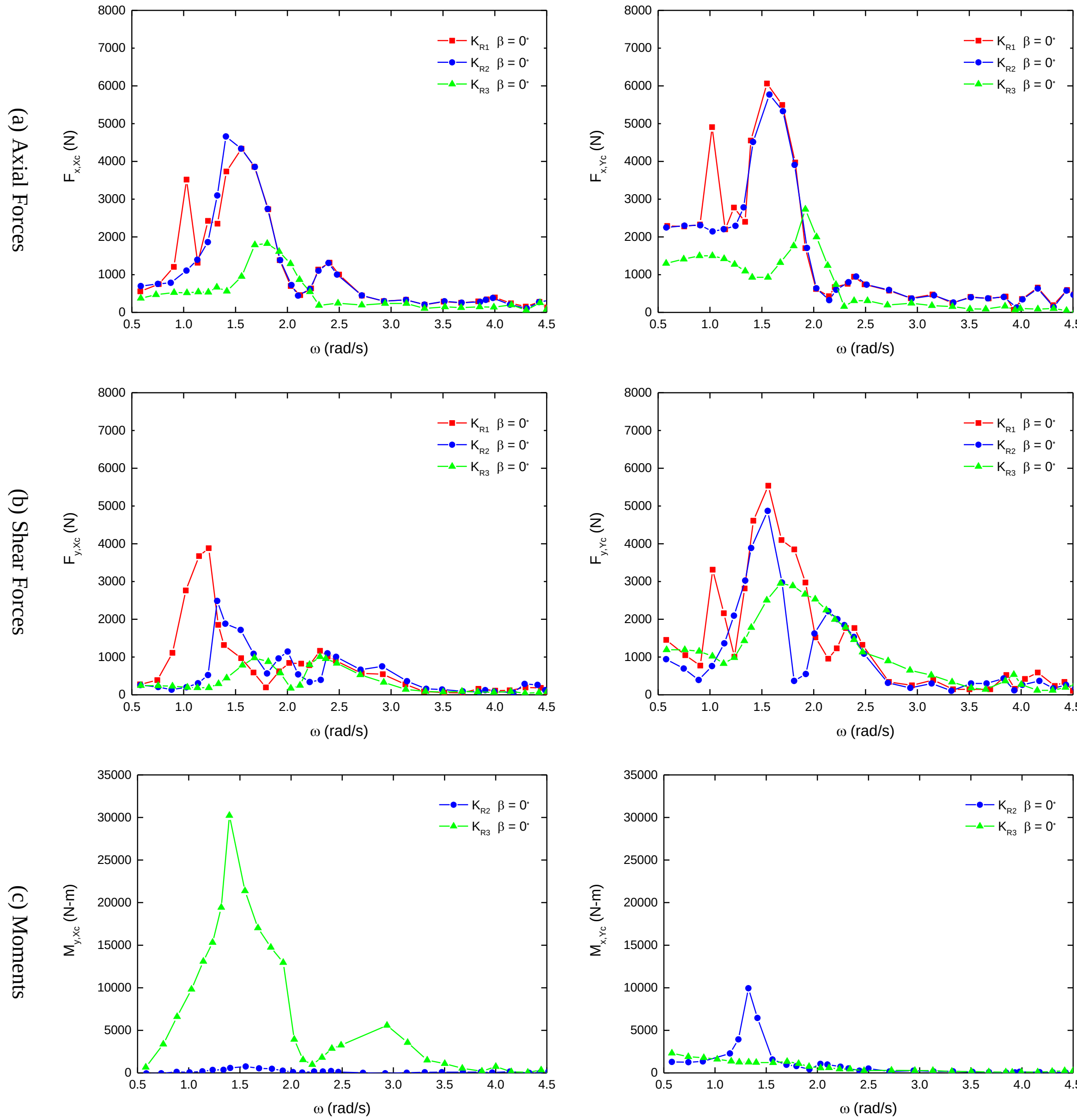
(c) Shear Forces

Note: *H/L* represents the wave steepness, where *H* is the incident wave height and *L* is the wave length.

Figure 13. Variation of Axial Forces and Shear Forces of CN1-CN4 as a Function of Incident Wave Frequencies (Adapted from Loukogeorgaki et al. (2014)).



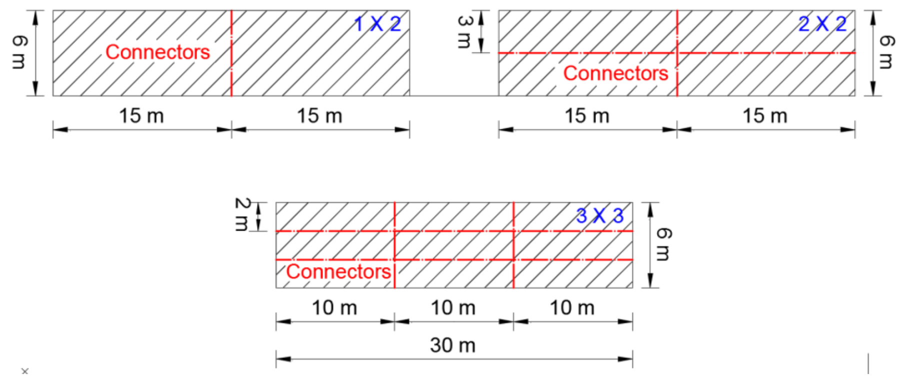
FS$_{3j}$ (3×3)	
Case	K_{Rj} (Nm/rad)
FS$_{31}$	0
FS$_{32}$	1.0E+3
FS$_{33}$	1.0E+5

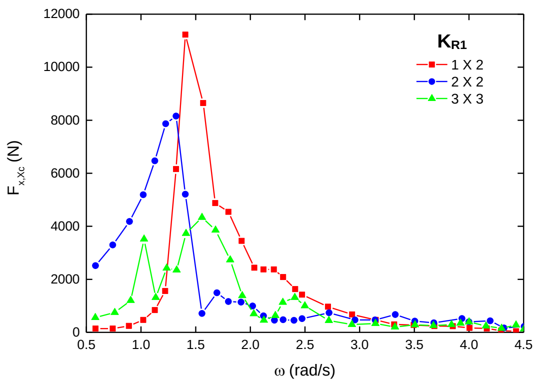


Connectors in the X-direction

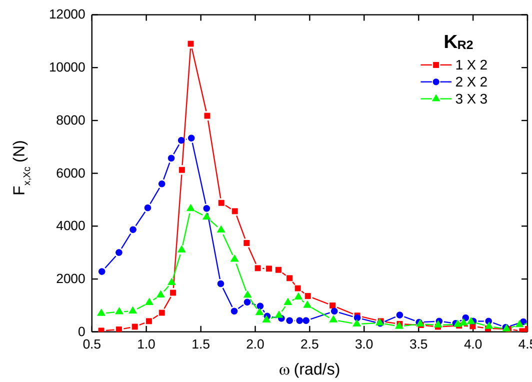
Connectors in the Y-direction

Figure 14. Connectors' Internal Forces of 3×3 Grid Type Floating Structures for Wave Angle β = 0° (Adapted from Michailides et al. (2013)).

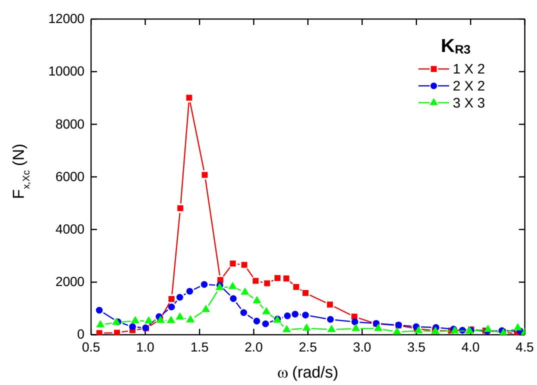




(a) K_{R1} = 0 Nm/rad

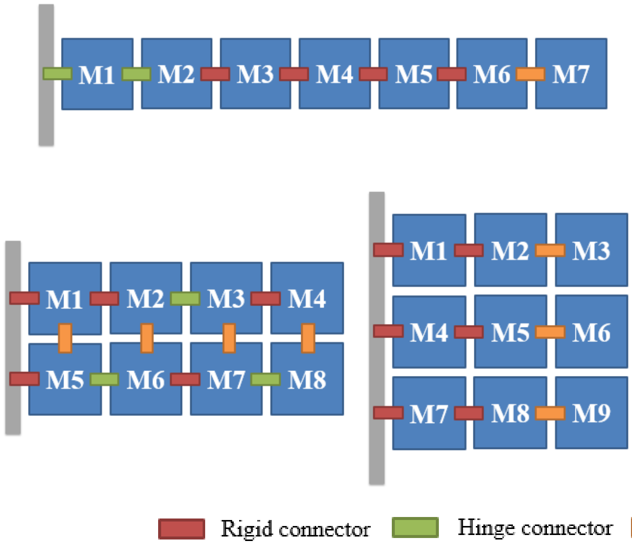


(b) K_{R2} = 1.0E+3 Nm/rad



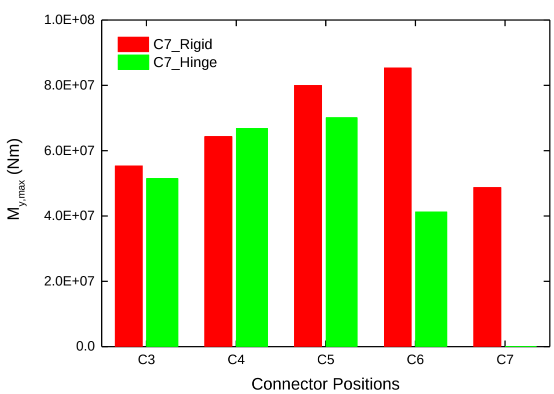
(c) K_{R3} = 1.0E+5 Nm/rad

Figure 15. Variation of Connectors' Axial Forces in the X-direction for Different Module Layouts (Adapted from Michailides et al. (2013)).

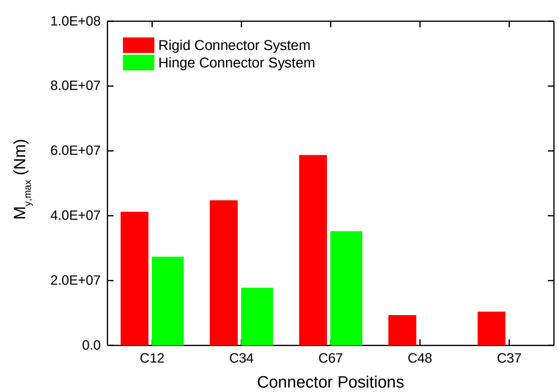


Module Layout	Configuration
one-line system	All fixed
	Hinge at C7
2 × 4 grid system	Fixed between two rows
	Hinge between two rows
3 × 3 grid system	All fixed
	Hinge at outermost modules

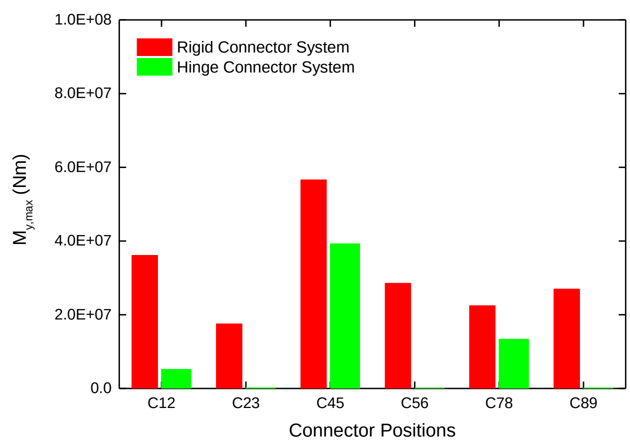
(a) Test module layout and connector arrangement



(b) One-line layout

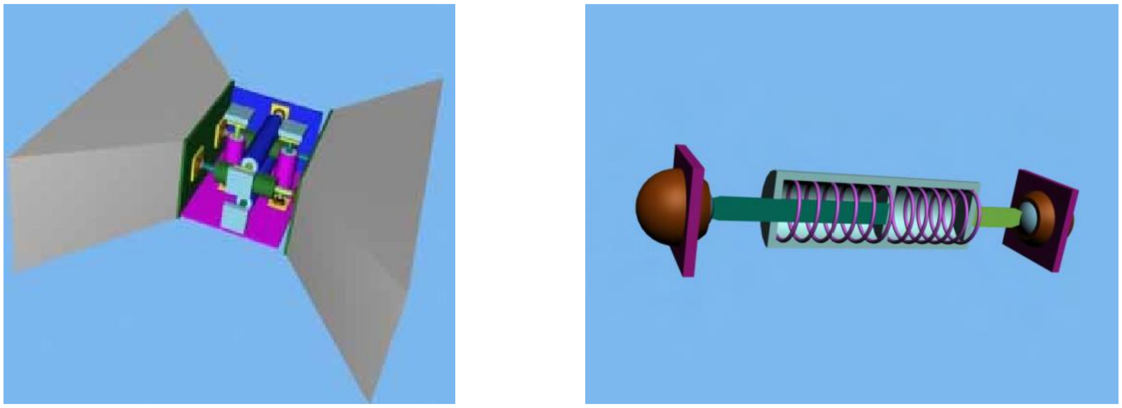


(c) 2 × 4 grid layout



(d) 3 × 3 grid layout

Figure 16. Maximum Bending Moments of Floating Structures with Various Module Layouts and Different Combination of Hinge and Rigid Connectors.



(a) Connector configuration (b) Ball and spring device

Figure 17. Flexible Connector System Proposed by Qi et al. (2015)

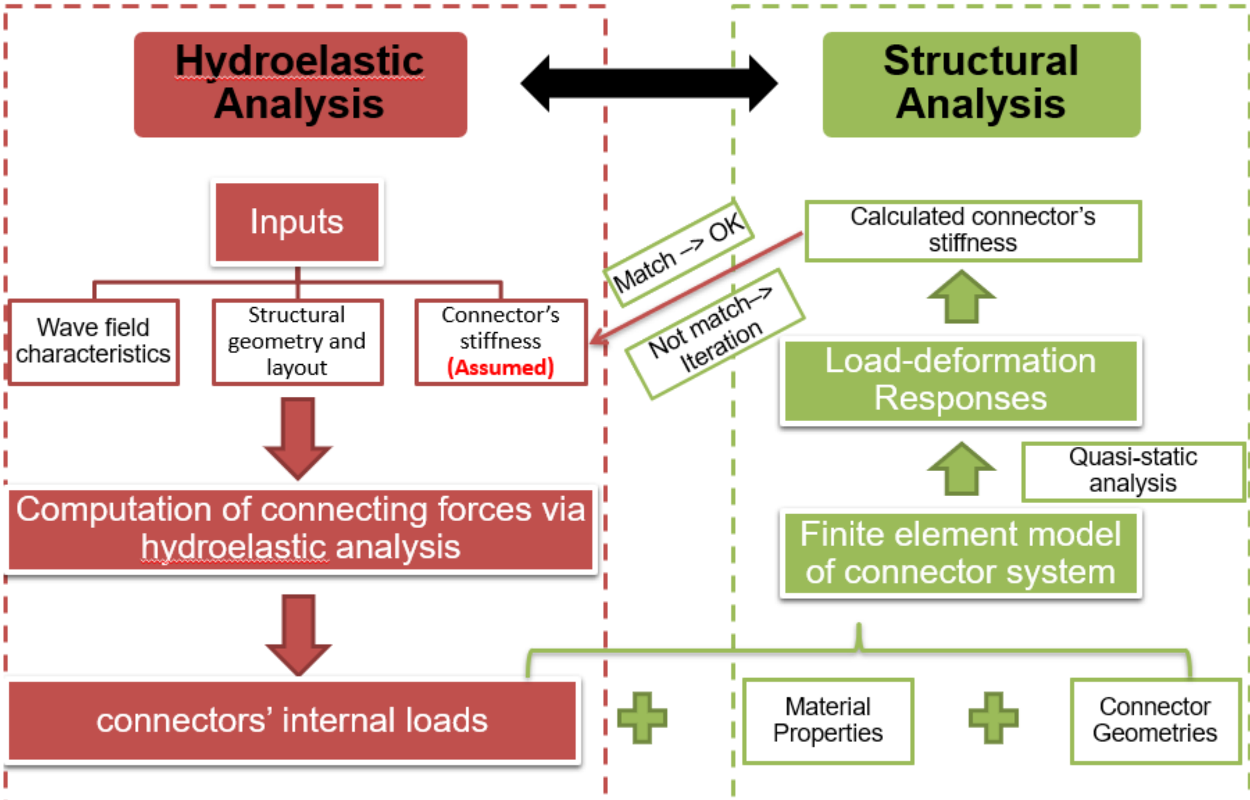
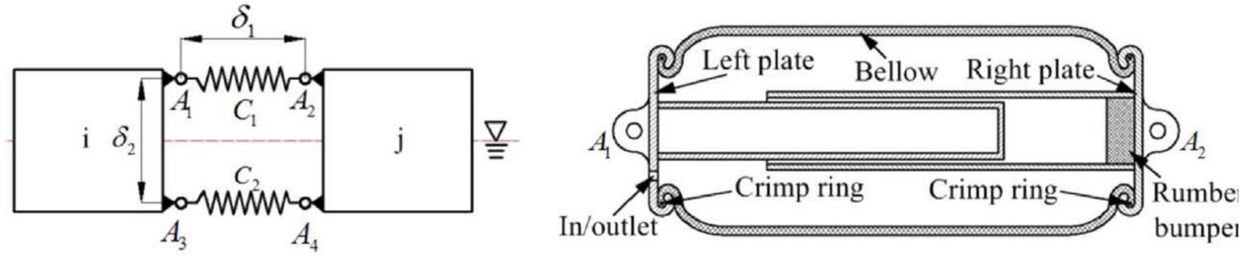


Figure 18. Flow of Determining Connector's Stiffness in Design Practice.



(a) Connection between adjacent modules (b) Air-spring connector

Figure 19. Active-control Connector System Proposed by Xia et al. (2016)