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Impact of Wave Directions on Connector Forces in Hexagonal Modular Floating Structure Networks

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ABSTRACT

This paper presents the development of the hexagonal modular floating structure (HMFS) connector network and the determination of the impact of the connector horizontal force using four types of configurations which are the U-shaped, VP-shaped, VV-shaped and centre layout which connect three hexagonal modules that form a network of connectors. The determination of the forces exerted on the connector from the wave motion highlights the importance of understanding dynamic load interactions between the HMFS. Simulation works were conducted for regular waves in the following directions: 0°,30°,45°,60°,85°, and 90°. The analysis takes into account the influences of various wave directions and HMFS configurations on the connector forces. The analysis shows that the connector force in the centre configuration and VV-shaped configuration is higher than the load in the other two HMFS configurations. The VV-shaped configuration, which has hexagonal vertices oriented towards the wave direction, experiences a greater connector force than the VP-shaped configuration, which aligns its hexagonal parallel side with the wave directions.

1. Introduction

The development and exploitation of the ocean have become significantly more diverse due to the growing human demand and advancements in ocean engineering technology as reported by Song *et al.,* [1] and Park *et al.,* [2]. The design of ocean structures has evolved from traditional ships to complex interconnected platforms for various functions such as space resources [3,4], ocean energy utilization, etc. The Very Large Floating Structures (VLFS) are being utilized extensively for maritime exploration, starting from the floating airport in Tokyo Bay and the performance stage in Singapore's Marine Bay [1]. Currently, the expansion of the global economy and the ongoing utilization of marine resources have increased offshore floating constructions such as port terminals, offshore wind energy, and offshore oil sector as reported by Park *et al.,* [2]. He *et al.,* [5] state that the huge bending moments generated during the application of single continuum floating structures and modular

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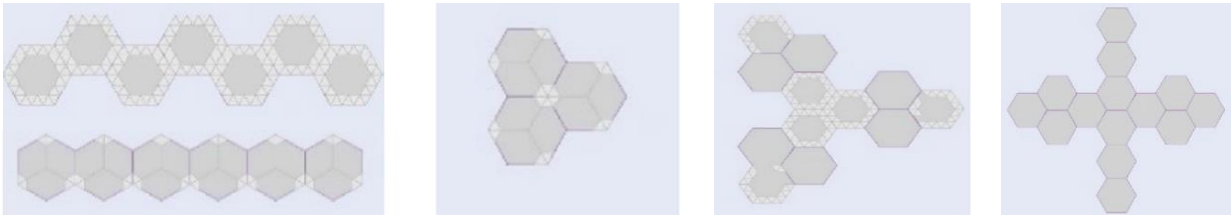
floating structures create a potential risk to structural integrity. A single floating structure with large sizes of floating structure could cause massive loads in structures; thus, the types of modular floating structures are preferred which have advantages for construction, transportation and deployment as stated by Watanabe *et al.,* [6].

The hydrodynamic performance of modular floating structures influenced by waves, tides and wind should be studied because it gives impacts to the safety and stability of modular floating structures. Xia *et al.,* [7] highlighted that the system stability of modular floating structures has been a critical issue in the design of VLFS it not only affected the safety but also the service life and maintenance cost of VLFS. Furthermore, the location of the central module, tail module and outer module in deciding the arrangement of the multi-floating structure gives effect to the motion characteristic of floating islands as stated by Park *et al.,* [2]. There are four arrangements of hexagonal modular floating structures proposed by Shihy [8] designed as floating cities: linear arrangement, circular arrangement, dynamically arrangement and orthogonal arrangement. The dynamically arrangement is illustrated with the combination of linear and circular arrangements, while the orthogonal arrangement expands the linear arrangement in an L- shaped layout shown in Figure 1.



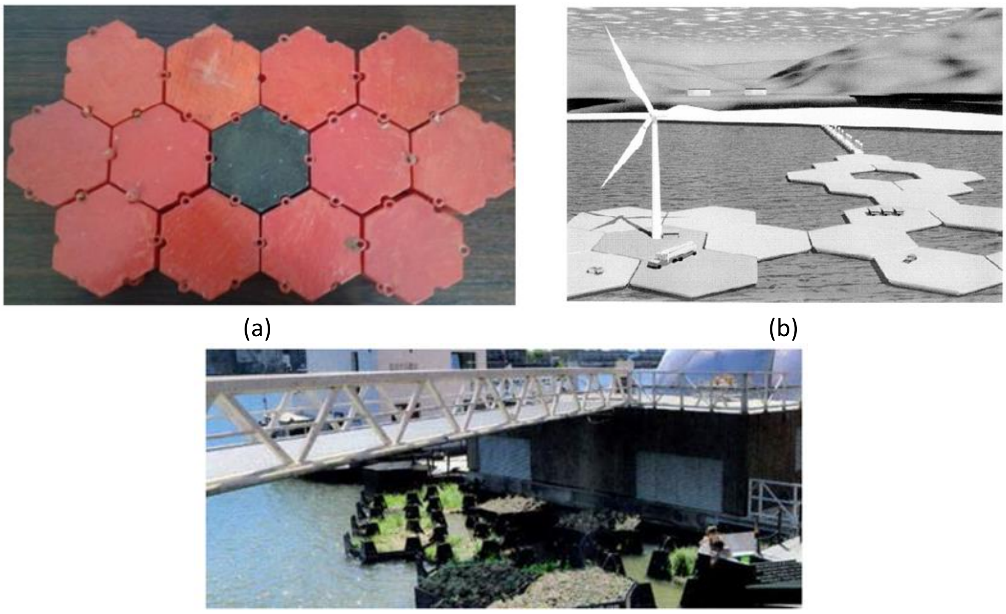
(a) (b) (c) (d)

Fig. 1. The four arrangements of hexagonal modular floating structures proposed by Shihy [8] functioning as floating cities: (a) linear arrangement (b) circular arrangement (c) dynamically arrangement (d) orthogonal arrangement

Lister and Muk-Pavic [4] proposed a sustainable artificial island concept for the Republic of Kiribati that applied the hexagonal modular floating structure in circular and U-shaped arrangements were U-shaped arrangements for easy shipping transportation. Stanković *et al.,* [9] also proposed the hexagonal modular floating structure for the Republic of Kiribati but with different combinations, such as the combination of circular and linear arrangements. Generally, many researchers proposed arranging initial modules in parallel on the side of hexagonal modules; however, differently, Ko [10] proposed the initial modules on the vertex sides of hexagonal modules. These different sides of hexagonal, such as parallel sides and vertex corners influence the arrangement of hexagonal modular floating structures.

Other than floating city purposes, the HMFS also have been implemented in other functionally such as breakwater, wind power plant and floating landscape functions as seen in Figure 2. Dwito Armono *et al.,* [11] arranged the HMFS conceptual design of the breakwater in a linear arrangement. Tetsuya Kogaki *et al.,* [12] applied the circular arrangement and the middle hollow of circular arrangement in his design of hexa-float function as large wind power plants. Şahbaz and Karabağ [13] proposed the Recycle Park which functions as a floating landscape built from material recycled from the waste in water in Rotterdam built in a circular arrangement.

Jiang *et al.,* [14] asserted that the internal forces generated in the connector significantly influenced the structural integrity during wave action. However, only a limited number of researchers have conducted numerical evaluations of these internal forces, which include module configuration, shallow water effects and incident wave periods. The trend of the connector load depends on the shape of the floating structure. The horizontal connector force trend of square modular floating structures proposed by Riggs and Cengiz Ertekin [15] shows that the horizontal connector force linked to five square modular floating structures is increasing gradually from 0^0 wave direction to 75^0 wave directions, decreasing sharply at 80^0 wave direction and the highest horizontal connector force is at 85^0 wave directions. The trend of horizontal connector force has also been similar to the rectangular modular floating structure that has been proposed by Ding *et al.,* [16], where the higher horizontal connector force at 85^0 wave directions connected three rectangular modular floating structures.



(a) (b) (c)

Fig. 2. The hexagonal HMFS also have been implemented in other functionally such as: (a) breakwater by Dwito *et al.,* [11], (b) wind power plant by Tetsuya *et al.,* [12], (c) floating landscape function by Stanković *et al.,* [13]

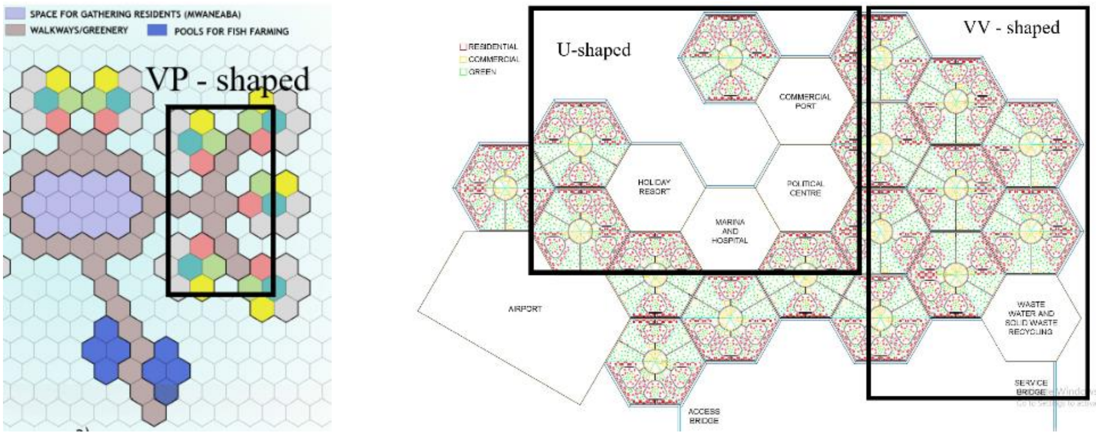
The higher horizontal connector force for the hexagonal modular floating structure at 0^0 wave direction has been discovered by Otto *et al.*, [17], Hongtao *et al.,* [18], and Hanani *et al.,* [19]. Otto *et al.,* [17] built a combination of triangular module that has 60^0 connector directions that create a big hexagonal module, then he asserted that to avoid a typical in-line environment with less than 30^0 spreading into wind, waves and current as it will give the higher connection loads. Hanani *et al.,* [19] studied five hexagonal modular floating structures linked together in a linear arrangement and discovered that the 0^0 wave direction gives a higher connector force and gradually reduces the horizontal connector force as the wave direction increases.

Therefore, the aim of this research is to determine the maximum horizontal connection load influence by various wave directions with varying HMFS arrangements. The hexagonal shape of a modular floating structure can create various designs due to it having six sides that can arranged without gaps. Hence, a suitable arrangement should be designed in the conceptual design of the modular floating structure, incorporating the impacts of connector load.

2. Methodology

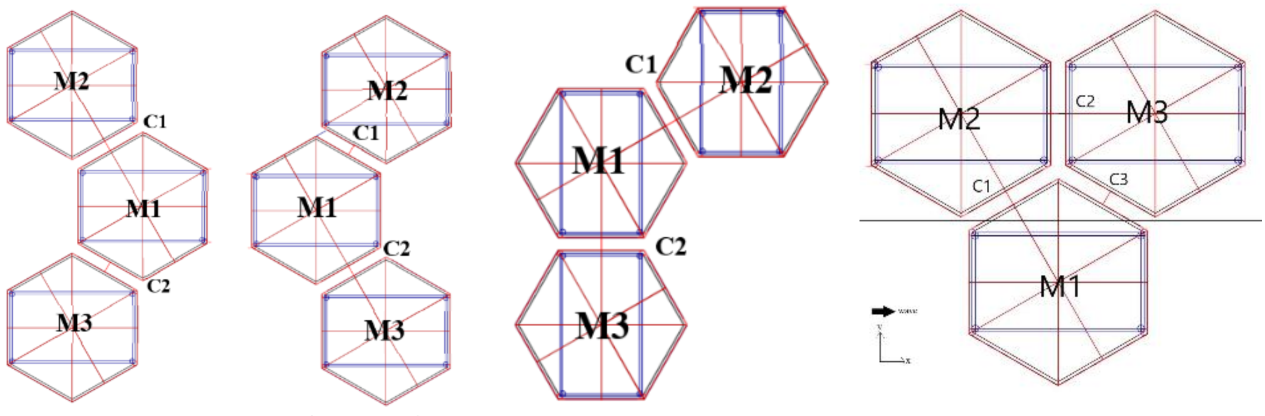
2.1 Conceptual Design of Hexagonal Modular Floating Structure (HMFS) System

The idea configuration of the HMFS system was through a literature review. The research adopted the concepts idea from Stanković *et al.,* [9] and Lister and Muk-Pavic [4], proposing four configurations of the HMFS system were proposed in this research: such as U-shaped, VP-shaped, VV-shaped and center arrangement. VP-shaped configurations that take into account the sides hexagonal and VV-shaped configurations present in vertices hexagonal shown in Figure 3. There are three hexagonal modules (M1-M3) interconnected with a ball connector for each configuration of the HMFS system as illustrated in Figure 4. The primary module is the M1 module, serving as the central axis of a symmetrical module configuration. The overall configuration is centered on M1, with M2 positioned above, and M3 organized below. The numbering of connectors also corresponds to the same ideology by continuing sequentially as the top (C1) and bottom (C2) as the numbering of hexagonal modules.



(a) (b)

Fig. 3. The idea of HMFS system arrangement from Stanković *et al.* [9] for VP -shaped and Lister and Muk-Pavic [4] for U-shaped and VV-shaped configuration



(a) (b) (c) (d)

Fig. 4. Four configurations of hexagonal modular floating structure (HMFS) utilized in the current study; (a) U-shaped, (b) VP-shaped (c)VV-shaped (d) center arrangement

The information on the hexagonal floating structure, connector and mooring was adopted by Li *et al.,* [20]. For this simulation, a ball connector has been selected connecting each hexagonal floating structure and moored with four tension legs to the seabed. The fenders have also been installed at the bottom edge of adjacent modules to avoid a possible collision. The information on the HMFS system is shown in Table 1.

Table 1
The information about the HMFS system

Details	Value	Unit
Side length, Height	20, 12	m
Water depth, Draft	80, 10	m
Mass	6000	t
Ixx= Iyy	9.6 x10^8	kg.m^2
Tension – leg dimension	D= 1.2; T=0.04; L = 70	m
Steel tension leg, E	2.1 x10^{11}	N/m^2
Stiffness of fenders	1.0 x 10^7	N/m
Adjacent distance	3	m
Ball connector linear rotational dampers (Ks)	4 x 10^9	Nms/rad
Ball connector Linear Rotational Springs	0	Nms/rad

2.2 Table Style and Format

The maximum horizontal force of each configuration was investigated under a regular sea condition (T=8s, H=2m) with various wave directions such as 0^0,30^0,45^0,60^0,85^0,90^0). The motion responses of each hexagonal and the maximum horizontal force under various wave directions were simulated using Ansys. The governing equation of the HMFS system in Ansys is as follows:

$$M_i \ddot{X}_i + C_i \dot{X}_i + K_i(X_i) = F_{i,wave} + F_{i,con} + F_{i,TLP} + F_{i,Fender} \quad (1)$$

where M_i, C_i and K_i are the mass matrix, radiation damping (with certain artificial damping usually applied to compensate for viscous fluid effects) and the hydrostatic restoring matrix, respectively. Xi (6-DOF) denotes the generalized displacement vector of the i-th module. $F_{i,wave}$, $F_{i,Con}$, $F_{i,TLP}$ and $F_{i,Fender}$ denote the matrix of the generalized wave force, the connector force, the tension matrix of tension legs and the impact force matrix of fender, respectively. The connector force between adjacent modules can be expressed as:

$$F_{i,con} = \sum_{j=1}^{7} (\varphi_{ij} K_{cij} \delta (X_i, X_j)) \quad (2)$$

where ϕ_{ij} denotes a topology matrix. The value of ϕ_{ij} is 1 when the i-th module is connected to the j-th module, otherwise, the value of ϕ_{ij} is 0. K_{cij} and $\delta(X_i,X_j)$ denote the connection stiffness matrix and the relative motion matrix between the i-th module and the j-th module, respectively. The total tension-leg force of the i-th module can be expressed as:

$$F_{i,TLP} = \sum_{j=1}^{4} E_i A_i \varepsilon_{ij} \quad (3)$$

where E_i denotes the elastic modulus. A_i denotes the sectional area of the tension leg of the i-th module. εij denotes the strain of the j-th tension leg of the i-th module. The possible bottom fender impact force $F_{i,fender}$ can be expressed as:

$$F_{i,fender} = \begin{cases} K_{fij} \;.\; \delta x, if\ \delta x(X_i, X_i) < -3\ m\ (contact) \\ 0 \qquad if\ \delta\ x(X_i, X_i) < -3\ m\ (contact) \end{cases} \quad (4)$$

where K_{fij} (1x10^7 N/m) is the bottom fender linear stiffness coefficient between the i-th module and the adjacent j-th module. $\delta x(X_i,X_j)$ is the relative bottom surge motion between the i-th module and the adjacent j-th module. If the negative relative bottom surge motion $\delta x(X_i,X_j)$ is smaller than the module gap (3m), the two adjacent modules will impacts on the bottom. Then, the contact force at the bottom fenders will be monitored.

3. Results and Discussion

The maximum horizontal connector force for interconnected three hexagonal modules at various wave directions in U-shaped is shown in Figure 5. The higher value of maximum Fx across various wave directions has been determined at 45^0 and 60^0 on connector C2. The oblique connection arrangement positions that the connector facing wave is closer to the 0^0 wave direction, resulting in an increased connector load for the hexagon floating structure as illustrated in Table 2. Mostly connector C2 has a higher compared to connector C1 because the first connector faced the wave force. The lowest value of Fx across different wave directions occurred at connector C1 on 60^0 wave directions. The U arrangement of three hexagonal modular floating structures presents two trends of maximum Fx values. Firstly, the maximum Fx value at 0^0 wave direction is similar, as the wave dynamics engage with each connector independently without a shielding effect. Secondly, the upper connector C1 has a lower value and the bottom connector C2 has a higher value.

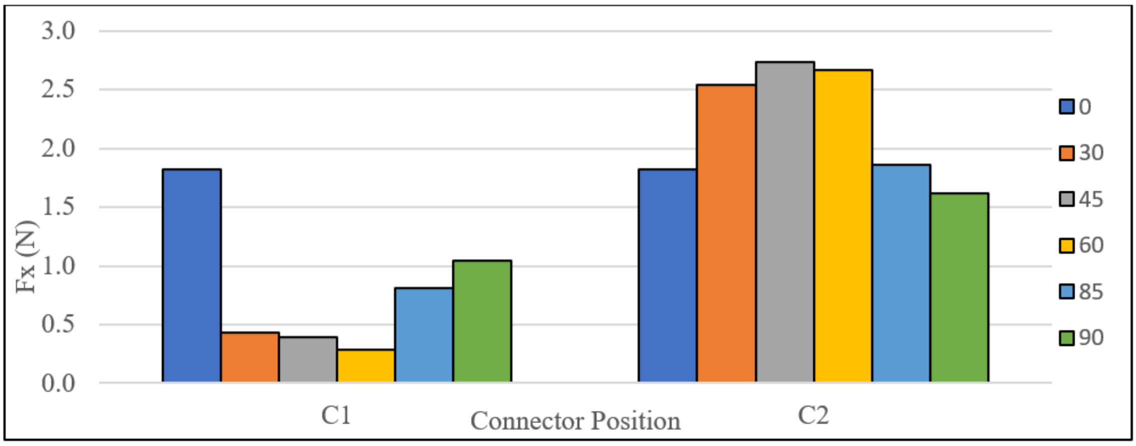


Fig. 5. Maximum horizontal force (Fx) of each connector for U-shaped configuration at various wave direction

Table 2
The sequential connector is oriented towards wave forces that shift influence by wave direction and the angle of the connector facing wave force for various wave directions in the 3U-shaped arrangement

Wave direction	Sequential connector facing wave force	Angle connector facing wave force	
		C1 (DC \)	C2 (VC /)
0^0	C1 = C2	120^0	60^0
30^0	C2, C1	85^0	45^0
45^0	C2, C1	65^0	15^0
60^0	C2, C1	60^0	0^0
85^0	C2, C1	25^0	-25^0
90^0	C2, C1	30^0	-30^0

*DC for diagonal angle direction of connector \
VC for vertical angle direction of connector /
P for parallel direction of connector –
= same time orientation wave direction

The highest maximum Fx value was 2.52 MN at connector C1, with a wave direction of 30^0 shown in Figure 6. The Fx value was the same by 1.83 MN for the 0^0 wave directions. The majority of connectors show higher values at connector C1, particularly at wave directions of 30^0, 45^0, and 60^0. Connector C2 exhibits the lowest maximum Fx value at wave direction 60^0 by 0.31 MN. The difference between the higher Fx value and the lower Fx value for wave directions of 30^0,45^0,60^0 was higher by a range of 84% to 88%. The hexagonal modular module was lined up with that of the top module (M2) and bottom module (M3) in a staggered layout. However, the connector between connectors C1 and C2 was not lined up in the same way, which affected the maximum Fx value. Connector C1 is oriented at a vertical angle, while connector C2 is oriented at a diagonal angle. Thus, two trends of the maximum Fx value in the 3VP arrangement indicate that the higher maximum Fx value was observed at wave directions of 30^0,45^0 and 60^0 for the vertical orientation of connector C1, whereas wave directions of 85^0 and 90^0 appear at diagonal connector orientation on connector C2. The higher horizontal connector force is higher in connector C1 because the angle connector facing wave force is nearer to the 0^0 wave direction compared to connector C2, although the connector C2 facing the incident wave initially shown in Table 3.

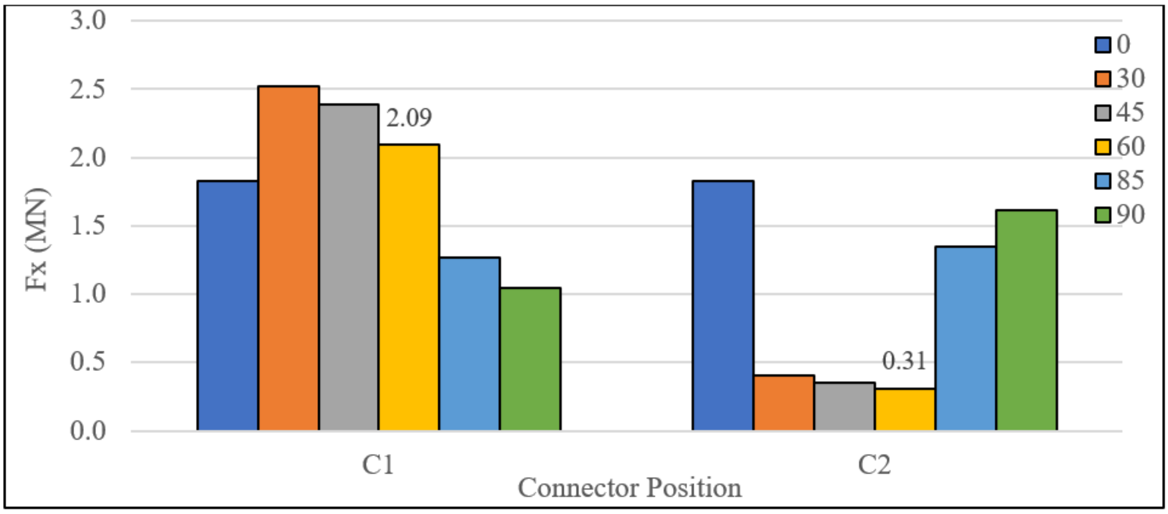


Fig. 6. Maximum horizontal force (Fx) of each connector for VP-shaped configuration at various wave direction

Table 3
The sequential connector is oriented towards wave forces that shift influence by wave direction and the angle of the connector facing wave force for various wave directions in 3VP-shaped arrangement

Wave direction	Sequential connector facing wave force	Angle connector facing wave force	
		C1 (VC /)	C1 (VC /)
0^0	C1 = C2	60^0	120^0
30^0	C2, C1	30^0	85^0
45^0	C2, C1	15^0	65^0
60^0	C2, C1	0^0	50^0
85^0	C2, C1	-25^0	25^0
90^0	C2, C1	-30^0	30^0

The highest maximum Fx value across different wave directions is 4.68MN on connector C1 at a 30^0 wave direction, configured in a staggered arrangement, whereas the lowest value is 0.42 MN at connector C2 at a 0^0 wave direction, arranged in a parallel configuration shown in Figure 7. The lower maximum of the Fx value at connection C1 occurs in the 90^0 wave direction, while at connector C2 it is in the 0^0 wave direction. This layout has a singular trend: the higher maximum Fx connector at C1, oriented in a staggered configuration, is in contrast with the lower value connector C2, which is aligned in a parallel direction. In addition, the horizontal connector force is higher in connector C1 due to its angle connector facing wave force being closer to the 0^0 wave direction compared to connector C2, despite the connector C2 starting orientation towards the incident wave as shown in Table 4.

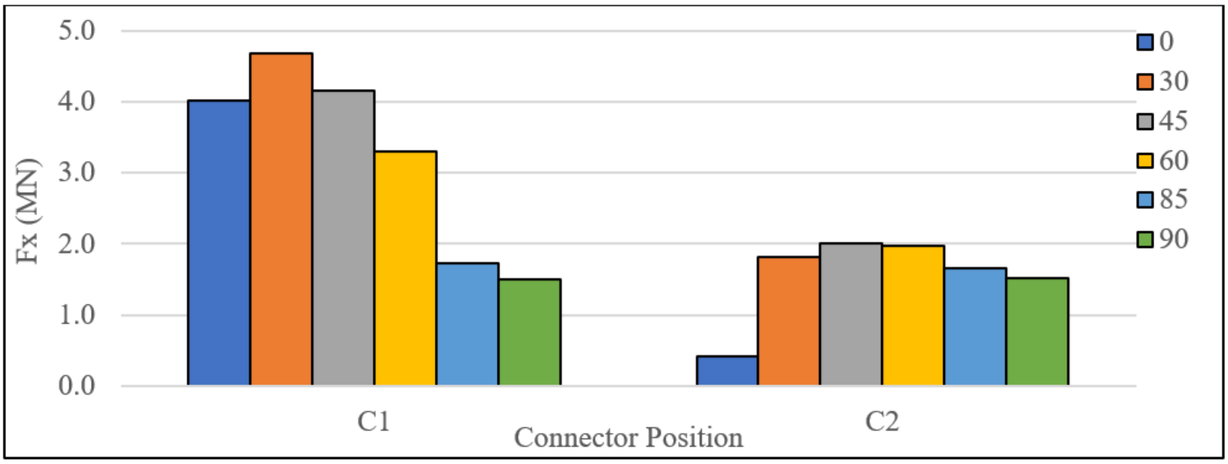


Fig. 7. Maximum horizontal force (Fx) of each connector for VV-shaped configuration at various wave direction

Table 4
The sequential connector is oriented towards wave forces that shift influence by wave direction and the angle of the connector facing wave force for various wave directions in the 3VV-shaped arrangement

Wave direction	Sequential connector facing wave force	Angle connector facing wave force	
		C1 (VC /)	C2 (P-)
0^0	C2, C1	30^0	90^0
30^0	C2, C1	-10^0	50^0
45^0	C2, C1	-20^0	40^0
60^0	C2, C1	-40^0	30^0
85^0	C2, C1	-55^0	5^0
90^0	C2, C1	-60^0	0^0

The higher Fx value is located on connector C2 in the wave direction of 00 in Figure 8. The majority of the higher Fx value occurs at connector C3, which is positioned at an angled vertical orientation for connectors for 45^0,60^0 and 85^0 of wave directions. The lowest Fx value is observed at connector C1, respectively at 60^0 wave directions. Most wave directions, with the exception of 90^0 wave direction, utilize the lower at connector C1. Two trends occur in the central arrangement of three interconnected hexagonal modules. Initially, the 00wave direction yields a higher Fx value compared to other wave directions for the hexagonal modular floating structure aligned with the parallel connector direction. Secondly, the angled vertical of the connector orientation exhibits the highest Fx value at wave directions of 45^0,60^0,85^0 and 90^0, while the diagonal connector orientation demonstrates the lowest Fx values across various wave directions. Other than that, the higher horizontal connector force occurs when the angle connector facing wave force is nearer to the 0^0 wave direction as shown in Table 5.

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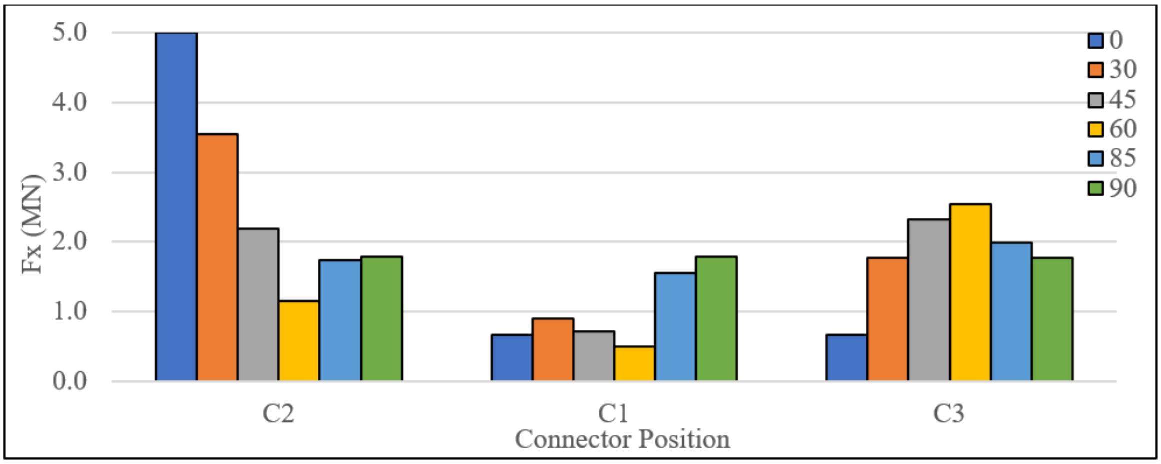

Fig. 8. Maximum horizontal force (Fx) of each connector for center configuration at various wave direction

Table 5
The sequential connector is oriented towards wave forces that shift influence by wave direction and the angle of the connector facing wave force for various wave directions in 3C arrangements

Wave direction	Sequential connector facing wave force	Angle connector facing wave force		
		C1 (DC\)	C2 (P-)	C3 (VC /)
0^0	C1, C2, C3	120^0	0^0	60^0
30^0	C1, C2=C3	80^0	-35^0	40^0
45^0	C1, C2, C3	70^0	-45^0	20^0
60^0	C1, C3, C2	55^0	-60^0	0^0
85^0	C1= C3, C2	35^0	-85^0	-25^0
90^0	C1= C3, C2	30^0	-90^0	-30^0

4. Conclusions

The present work proposes a hexagonal modular floating structure (HMFS) connected to three modules with a ball connector. The multi-floating structure hydrodynamics interaction effect and connector coupling effect were considered. The effect of wave direction and direction of the connector on the different arrangements of HMFS was investigated. The conclusion has been summarized as follows:

i. The connector orientated towards the 0^0 wave direction experiences higher horizontal connector force for hexagonal shape configurations compared to other wave directions, thereafter, an increase in wave direction reduces the horizontal connector force.
ii. The connector associated with the initial module confronting the wave force will experience a higher horizontal connector force.
iii. The connector orientation applied in the HMFS configurations is 60^0, leading to an alteration in wave direction relation to the connector, even though the HMFS configurations remain unchanged.
iv. The variation in wave direction is also should take note of the alteration of the configurations of hexagonal modules in relation to the incident wave within a similar HMFS arrangement.
v. However, the wave direction of 0^0 directed towards the connector produces higher horizontal force, despite the initial modules being oriented to confront the wave force. Based on these five criteria, the designer could have predicted the higher connector early.

vi. The connector force in the centre configuration and VV-shaped configuration is higher than the load in the other two HMFS configurations.
vii. The VV-shaped configuration, which has hexagonal vertices oriented towards the wave direction, experiences a greater connector force than the VP-shaped configuration, which aligns its hexagonal parallel side with the wave directions.

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