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# Experimental Study and Numerical Analysis of Floating Crane Catamaran Mooring Tension in Intact and Damage Conditions Using Time-Domain Approach

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## ABSTRACT

*Floating Crane Catamaran equipped with a mooring system to keep stable while operating. During operation, wave load causes tension on the mooring system. In this study, the tension of the mooring system was analyzed using experimental studies and numerical analysis with intact and damaged mooring conditions. Experimental studies were carried out by simulating a physical model in the Ocean Basin Maneuvering Laboratory, BTH-BPPT. While numerical using related software. Mooring tension analysis is carried out using the frequency domain approach which refers to the API RP 2SK rules. The sum of the average tension, significant low frequency tension and maximum wave frequency tension is the maximum tension of the mooring system. The low frequency tension and wave frequency tension is obtained by the low-band-pass filter process. The stochastic value is obtained by the FFT of low frequency and wave frequency tension. The results of maximum tension from experimental and numerical at intact conditions, wave headings 90°, Hs 2.5 m, are 373.7 kN and 441.6 kN and at Hs 6.37 m are 565.6 kN and 1741.5 kN. In the damaged condition, wave heading 90°, Hs 2.5 m, the maximum tension is 863.9 kN and 2113.3 kN.*

**Keywords:** *Floating crane catamaran, Mooring tension, Intact, Damaged.*

## 1. INTRODUCTION

Floating Crane Catamaran hereinafter referred to as FCC is an innovative catamaran hull vessel equipped with facilities such as an Accommodation Working Barge. Catamaran hull ships have better stability than single hull ships. The FCC has a function as a means of transportation, installation, and decommissioning of offshore platform components. During offshore operation, the catamaran floating crane is moored. Tethering aims to limit the movement of the structure from the desired position so that the structure can operate safely FCC is moored using a spread mooring type mooring system, the spread mooring configuration used in the FCC when operating is the 8-mooring line configuration. In this study, an analysis of the FFC mooring tension was carried out in the intact and damaged conditions. The intact condition is a condition when the structure operates with a fully functional mooring line or when the mooring line is not broken. While the damaged condition is the condition when the structure operates with the mooring rope that is broken. The maximum tension of the mooring line generated in each condition is then compared with the API RP 2 SK criteria to determine whether the intact and damaged mooring line tension is within safe limits or not. In the intact condition, the maximum mooring line tension must meet the safety factor criteria ≥ 1.67. In damaged condition, the maximum mooring rope tension must meet the safety factor criteria ≥ 1.25.

## 2. BASIC THEORY

### 2.1 Floating Crane Catamaran

The floating catamaran crane is an innovative catamaran hull vessel that equipped with facilities such as an accommodation working barge complete with a crane and helideck. The catamaran has two hulls connected by a bridging structure. During operation, the floating catamaran crane moored using a spread mooring. The purpose of mooring is to limit the horizontal movement of the floating structure from the desired position so that the structure can operate safely.

### 2.2 Mooring Stiffness

The stiffness of the mooring line can be calculated based on the Hooke's law. Hooke's law equation explains that the tension force that occurs is the result of multiplying the stiffness and increasing the length of the rope. Hooke's law equation is shown in equation 1 below.

$$F = K.dx \quad (1)$$

Where $F$ is tension force (kN), $K$ is stiffness (N/m), and $dx$ is increasing the length of the rope (m).

### 2.3 Stochastic of Maximum Mooring Tension

Analysis of the maximum mooring tension was carried out using the frequency domain approach which refers to the API RP 2 SK rules [1,8]. Based on these rules, the maximum mooring rope tension is the sum of the average tension, the significant low frequency tension and maximum wave frequency tension [1]. Equation 2 shows the formula for maximum mooring tension.

$$T_{max} = T_{mean} + T_{wfmax} + T_{lfsig} \quad (2)$$

Where $T_{max}$ is maximum tension (kN), $T_{mean}$ is average tension (kN), $T_{wfmax}$ is maximum wave frequency tension (kN), and $T_{lfsig}$ is significant low frequency tension (kN).

Tension at wave frequencies and low frequencies represented by narrow band gaussian. Stochastic values are calculated from the area under the response spectrum or probability density which is the root value of the variance ($m_0$) or the standard deviation value [4]. Based on API RP 2 SK, the value of significant low frequencies tension is calculated using equation 3.

$$T_{lfsig} = 2\sqrt{m_{0lf}} \quad (3)$$

Where $T_{lfsig}$ is significant low frequencies tension (kN), and $M_{0lf}$ is variance of low frequency tension ($kN^2$).

The maximum wave frequency tension is obtained from the probability of occurrence of 1 maximum response every 1000 responses [7]. Thus, the maximum wave frequency tension can be calculated by equation 4.

$$exp\left\{-2\left(\frac{T_{wfmax}}{T_{wfsig}}\right)^2\right\} = \frac{1}{1000}$$
$$T_{wfmax} = 1.86\, x\, T_{wfsig}$$
$$T_{wfmax} = 1.86\, x\, 2\, x\sqrt{m_{0wf}} \quad (4)$$

Where $T_{wfmax}$ is maximum wave frequency tension (kN), $T_{wfsig}$ is significant wave frequency tension (kN), and $M_{0wf}$ is varian of wave frequency tension ($kN^2$).

### 2.4 Mooring Safety Factor Criteria

The mooring safety factor is a safe limit (permit limit) for the operation of a moored offshore floating building system by considering the maximum tension that occurs in the mooring system. The value of mooring tension must meet the safety factor criteria/limits. The criteria for mooring safety factor in this study are based on the API RP 2 SK rule which is described in Table 1 below.

Table 1. Mooring Safety Factor API RP 2 SK

| Condition | Analysis Method | Safety Factor |
|---|---|---|
| Intact | Dynamic | ≥ 1.67 |
| Damaged | Dynamic | ≥ 1.25 |

The mooring safety factor value is obtained by comparing the minimum breaking load value of the mooring line with the maximum tension of the mooring line. Equation 5 shows the formula for mooring safety factor.

$$Safety\ Factor = \frac{Minimum\ Breaking\ Load}{Maximum\ Tension} \quad (5)$$

## 3. RESEARCH METHODOLOGY

### 3.1. Experiment and Numerical Vessel Modelling

#### 3.1.1 Experiment Modelling

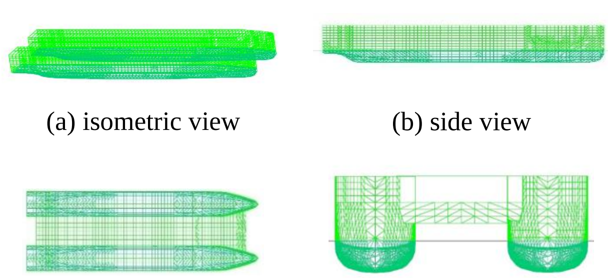
The experimental model of floating crane catamaran that was used in this study is a physical model with a scaling size of 1: 36. Scaling is used in such a way as to adjust the capacity of the available test pool. Also, in scaling it is necessary to pay attention to the similarity of the geometric, kinematic, and dynamic aspects of the experimental model with the numerical model [2]. Table 2 shows the main data for the target model in full scale and the experimental model with a scale model of 1: 36.

Table 2. Principle Dimension

| Parameter | Full Scale | Scale Factor | Model Scale |
|---|---|---|---|
| Load (m) | 111 | λ | 3.08 |
| LWL (m) | 111 | λ | 3.08 |
| Lpp (m) | 108 | λ | 3.00 |
| B (m) | 37.8 | λ | 1.05 |
| H (m) | 14.4 | λ | 0.4 |
| T (m) | 4.7 | λ | 0.13 |
| Displacement (ton) | 8464 | λ³ | 0.181 |

#### 3.1.2 Numerical Modelling

The numerical method of structural modeling was carried out using MOSES and Maxsurf software. Maxsurf software is used to model the principle dimension vessel according to the full-scale model target. Then take the Maxsurf model mesh marker which is then used as a model reference for the MOSES vessel. The numerical model is shown in figure 1.



(a) isometric view (b) side view

(c) top view (d) bow view

Figure 1. Hull modeling of floating crane catlamaran

After the numerical model is formed, the model validation is carried out. The model validation in table 3 is carried out to ensure the accuracy and suitability of the numerical structure modeling that has been carried out with the experimental structure. The modeling error tolerance used is 5%.

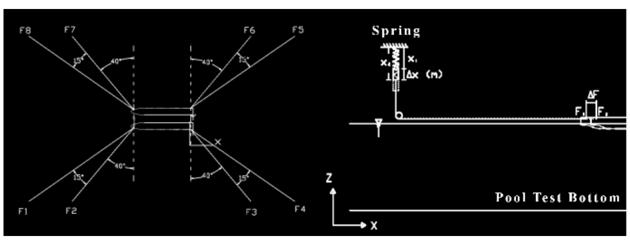
Table 3. Numerical Model Validation

| Parameter | Experiment | Numerical | Error | Note |
|---|---|---|---|---|
| LoA (m) | 111 | 111 | 0 % | OK |
| LWL (m) | 111 | 111 | 0 % | OK |
| Lpp (m) | 108 | 108 | 0 % | OK |
| B (m) | 37.8 | 37.8 | 0 % | OK |
| H (m) | 14.4 | 14.4 | 0 % | OK |
| T (m) | 4.7 | 4.7 | 0 % | OK |
| Displacement (ton) | 8464 | 8571.4 | 0.86 % | OK |

## 3.2 Experiment and Numerical Mooring Modelling

### 3.2.1 Experiment Modelling

The mooring system configuration in the experimental study is horizontal taut mooring as in Figure 2 below:




(a) top view (b) side view

Figure 2. Experiment Mooring Configuration

The mooring line material used in the experimental study is a combination of stainless-steel slings and springs. In the experimental method, a sling with a load capacity of 30 lbs or 13.6 kg is used (scale model), meaning that there is no change in the length of the sling if the load is still below 30 lbs or 13.6 kg. The maximum stress during the experiment occurred in the damaged scenario, Hs = 6.37 m, with a tension value of 863.87 kN (full scale) or 1,841 kg (scale model).

The maximum stress during the experiment does not exceed the sling strength limit so that the stiffness that acts on the mooring system in the experimental method only depends on the spring stiffness because only the spring experiences a change in length. Spring stiffness is obtained by the spring calibration process. Calibration is done by loading a spring model scale with a load of 250 gr to 2 kg. The loading causes a change in the length of the spring. By comparing the load to the change in length, the stiffness can be found (equation 1). The spring calibration shows a linear trendline with an $R^2$ value of 0.99995. Table 4 shows the 8 spring stiffnesses obtained from the calibration process.

Table 4. Spring Stiffness

| Description | Model Scale | Full Scale |
|---|---|---|
| | Stiffness (N/m) | Stiffness (kN/m) |
| Spring 1 | 44.334 | 58.89 |
| Spring 2 | 44.015 | 58.47 |
| Spring 3 | 43.576 | 57.88 |
| Spring 4 | 43.450 | 57.72 |
| Spring 5 | 43.925 | 58.35 |
| Spring 6 | 44.007 | 58.45 |
| Spring 7 | 44.204 | 58.72 |
| Spring 8 | 43.258 | 57.46 |
| **Average** | **43.846** | **58.25** |

It was found that the average stiffness value of spring was 58.25 kN / m (full scale). The spring stiffness is hereinafter referred to as the mooring rope stiffness in the experimental method.

### 3.2.2 Numerical Modelling

Catenary spread mooring is a type of mooring system used in numerical models because, in reality, a floating crane catamaran is a mobile unit with a short-time operation. In a short time operation, link configuration is not used because the configuration installation costs a lot of money. Based on these differences in configuration, the numerical mooring system must be modeled with mooring system properties that are as similar as possible to the experimental method.

The pretension and stiffness of the experimental mooring system are reference properties in modeling the numerical mooring system. In identifying the stiffness of the mooring rope, we first identify the mooring tension for each excursion vessel. In the experimental method, it is known that the stiffness value is 58.25 kN / m which means for each meter vessel excursion in Figure 2 (b). produces a tension of 58.25 kN. The assumptions used are: [9,11]

- Vessel excursion are inline with 2D local ordinat (X-Z) of mooring line
- No back mooring line considered
- Dynamic effect in the mooring lines are ignored
- Flat Seabed Horizontal
- Friction on the seabed is ignored

The assumption [9,11] is also used to model the experimental method of mooring line. Numerical mooring line iteration was carried out with the help of ORCAFLEX software with the catenary static analysis approach formulated by Faltinsen [6]. In the numerical model, iteration is carried out as shown in Figure 3.

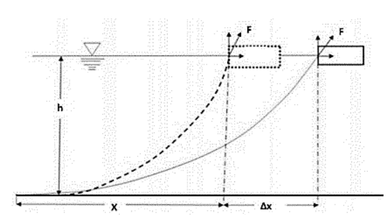


Figure 3. Catenary Mooring Analysis

Iteration is done by varying the diameter of the mooring rope. Meanwhile, the length of the rope, the horizontal distance and the type of rope are used the same value. Variations were carried out on one variable in order to determine the effect of one independent variable on mooring line tension [10]. Figure 4 is the results of the mooring tension – excursion iteration.

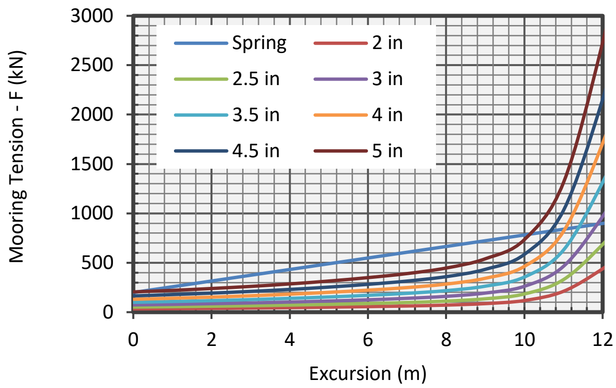



Figure 4. Mooring Tension – Excursion

At this condition, tension at 0 m vessel excursion is the pretension value. Those were the starting point of analysis. Pretension in the catenary mooring system (numerical) is the weight of the suspended mooring line. While the horizontal taut mooring system (experiment) is the result of the spring set up on the anchor pole.

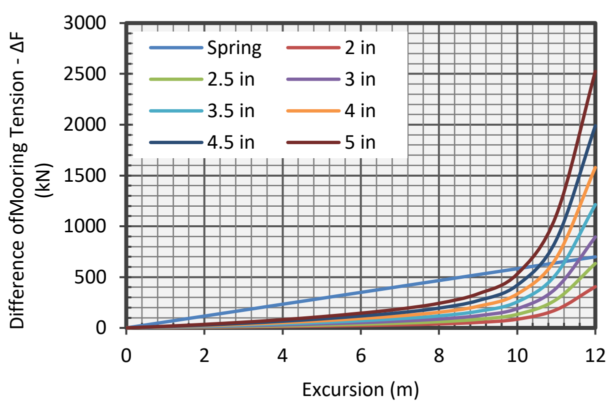



Figure 5. Difference of Mooring Tension – Excursion

The difference of mooring tension for each vessel excursion is obtained by calculating the gradually in mooring tension for each excursion vessel to the value of the initial tension(pretension). Spring (taut mooring) has a linear mooring tension trendline, while catenary mooring has an exponential mooring tension trendline. Mooring stiffness value of each excursion can be found by using hooke's law iteration (equation 1) see at (table 5, figure 6)

Table 5. Mooring Stiffness - Excursion

| Δx | Mooring Stiffness K (kN/m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (m) | Spring | 2 in | 2.5 in | 3 in | 3.5 in | 4 in | 4.5 in | 5 in |
| 1 | 58.2 | 2.6 | 4.0 | 5.8 | 7.9 | 10.3 | 13.0 | 16.2 |
| 2 | 58.2 | 2.8 | 4.3 | 6.2 | 8.5 | 11.0 | 14.0 | 17.4 |
| 3 | 58.2 | 3.0 | 4.7 | 6.7 | 9.1 | 11.9 | 15.1 | 18.7 |
| 4 | 58.2 | 3.2 | 5.1 | 7.3 | 9.9 | 12.9 | 16.3 | 20.3 |
| 5 | 58.2 | 3.5 | 5.5 | 7.9 | 10.8 | 14.1 | 17.8 | 22.1 |
| 6 | 58.2 | 3.9 | 6.0 | 8.7 | 11.8 | 15.4 | 19.5 | 24.2 |
| 7 | 58.2 | 4.3 | 6.6 | 9.5 | 13.0 | 16.9 | 21.4 | 26.5 |
| 8 | 58.2 | 4.8 | 7.6 | 10.8 | 14.7 | 19.2 | 24.3 | 30.3 |
| 9 | 58.2 | 6.0 | 9.3 | 13.3 | 18.1 | 23.6 | 29.8 | 37.3 |
| 10 | 58.2 | 8.5 | 13.3 | 18.8 | 25.6 | 33.3 | 42.0 | 53.0 |
| 11 | 58.2 | 16.2 | 25.3 | 35.5 | 48.1 | 62.5 | 78.7 | 100.7 |
| 12 | 58.2 | 33.8 | 52.8 | 74.6 | 101.1 | 131.5 | 165.8 | 210.4 |

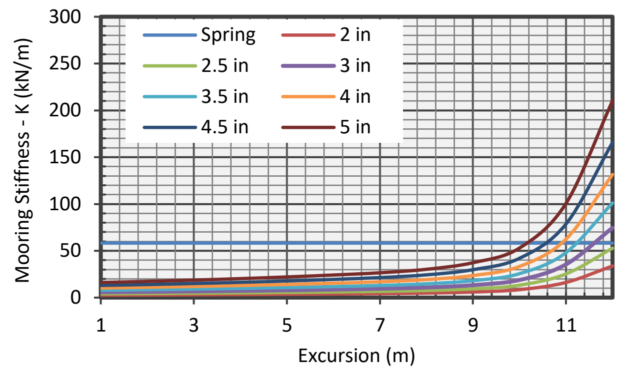



Figure 6. Mooring Stiffness - Excursion

The different configurations produce different experimental and numerical mooring stiffness patterns. Therefore, numerical mooring line properties modeled with as closely as possible to the experimental model. Based on experimental method, the pretension value was 198 kN. While the results of the iteration, the mooring rope specifications that are close to the pretension value are 6x19 wire with wire core ropes with specifications as in table 6.

Table 6. Mooring Properties

| Properties | Value | Unit |
|---|---|---|
| Diameter | 127 | mm |
| | 5 | inch |
| Weight | 0.631 | kN/m |
| Modulus Young | 113000000 | kN/m2 |
| Stiffness | 651309.1 | kN |
| MBL | 10215.4 | kN |
| Horizontal Distance | 320 | m |
| Length | 342.9 | m |
| Pretension | 204.8 | kN/m |

## 4. ANALYSIS RESULTS AND DISCUSSION

### 4.1 Time History Mooring Tension

Dynamic analysis of the experimental model was carried out in the MOB BTH-BPPT pool while the numerical model was carried out on the MOSES software. The test duration was carried out for 30 minutes (1800 seconds).

The scenario analysis was carried out 3 times, all loading in the beamseas direction (90°). Scenario I, has significant wave (Hs) 2.5 m intact condition. Scenario II with Hs 6.37 m in intact condition. Scenario III with Hs 6.37 m in damaged conditions. Figure 7 is the result of the first 1000 second mooring system tension of the experimental method in scenario I while figure 8 is the result of the first 1000 second mooring system tension of the scenario I numerical method

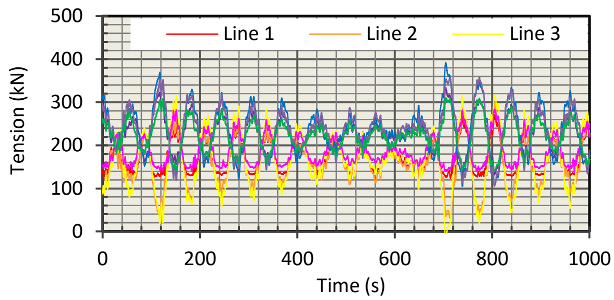



Figure 7. Time History Tension of Scenario I Experiment

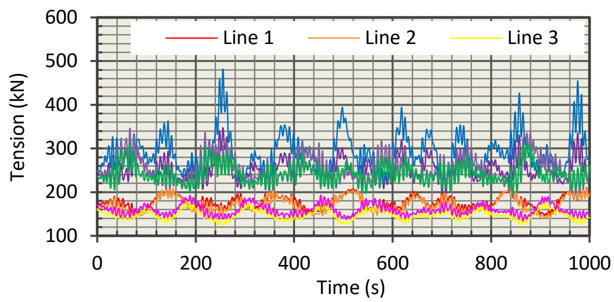



Figure 8. Time History Tension of Scenario I Numerical

The mooring tension that has been obtained is analyzed using the frequency domain approach. The approach used refers to the rules of API RP 2 SK as in equation 2 where there are components of low frequency and wave frequency tension.

### 4.2 Filtering, FFT, & Calculate Tension Component

The mooring tension at low frequencies is obtained by the low-pass filter (LPF) process and the mooring tension at the wave frequencies is obtained by the bandpass filter (BPF) process. A low-pass filter (LPF) is a filter method that picks up a signal with a frequency lower than the selected cutoff frequency or attenuates a signal with a frequency higher than the cutoff frequency. Band-pass filter (BPF) is a filter method that picks up a signal with a frequency higher than the selected cutoff frequency or attenuates a signal with a frequency lower than the cutoff frequency. The cutoff limit for the mooring line tension signal is the value of the wave encounter period. In this analysis, the Pierson Moskowitz wave spectra were used [5]. (figure 9)

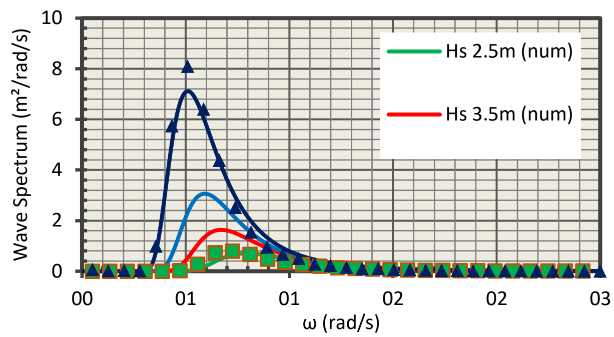



Figure 9. P-M Wave Spectrum

The value of the Pierson Moskowitz encounter period varies for each significant wave height parameter as shown in Table 7.

Table 7. Wave Encounter Periode

| Hs (m) | Encounter Periode (rad/s) |
|---|---|
| 2.5 | 0.38 |
| 3.5 | 0.34 |
| 4.5 | 0.3 |
| 6.37 | 0.26 |

After finding the value of the encounter period, using MATLAB software, the filtering process and the FFT of the mooring tension at low frequencies and wave frequencies could be done. Figure 10 show the results of the FFT tension at low frequency for the scenario I experimental methods. Figure 11 show the results of the FFT tension at the wave frequency for the scenario I experimental methods.

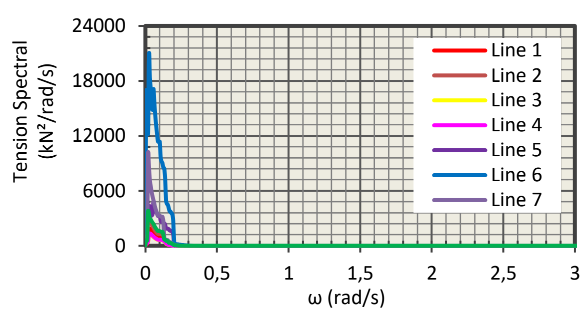



Figure 10. Low Frequency Spectral Tension Scenario I

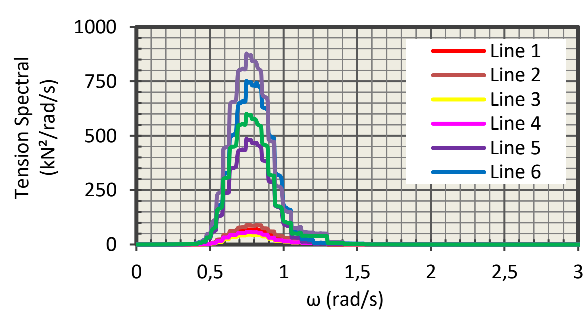



Figure 11. Wave Frequency Spectral Tension Scenario I

From the results of the FFT low-frequency tension, the stochastic value of significant low frequencies tension can be calculated using equation 3. The result are shown in Table 8.

Table 8. Significant Low Freq. Tension

| Mooring Line | Significant Low Frequency Tension (kN) | | | | | |
|---|---|---|---|---|---|---|
| | Experimental Scenario | | | Numerical Scenario | | |
| | I | II | III | I | II | III |
| 1 | 72.2 | 103.8 | 148.8 | 25.2 | 130.3 | 111.9 |
| 2 | 102.1 | 174.7 | 288.7 | 30.1 | 139.6 | 159.1 |
| 3 | 128.4 | 196.9 | 319.0 | 20.8 | 107.5 | 101.3 |
| 4 | 69.2 | 94.7 | 95.2 | 21.3 | 108.7 | 84.5 |
| 5 | 75.0 | 123.7 | 199.5 | 48.1 | 144.5 | 119.2 |
| 6 | 107.0 | 170.3 | 260.3 | 90.5 | 414.7 | 467.1 |
| 7 | 103.4 | 180.3 | 0 | 48.6 | 214.6 | 0.0 |
| 8 | 72.9 | 123.5 | 476.9 | 33.6 | 210.7 | 467.7 |

From the results of FFT low-frequency tension, the stochastic value of significant low frequencies tension can be calculated using equation 4. The results are shown in Table 9.

Table 9. Maximum Wave Freq. Tension

| Mooring Line | Maximum Wave Frequency Tension (kN) | | | | | |
|---|---|---|---|---|---|---|
| | Experimental Scenario | | | Numerical Scenario | | |
| | I | II | III | I | II | III |
| 1 | 28.2 | 94.3 | 86.8 | 19.6 | 40.4 | 31.5 |
| 2 | 35.8 | 147.5 | 133.6 | 21.7 | 44.3 | 53.1 |
| 3 | 37.7 | 146.7 | 111.2 | 15.6 | 38.5 | 40.6 |
| 4 | 22.4 | 74.7 | 39.2 | 17.3 | 35.6 | 39.1 |
| 5 | 24.1 | 105.5 | 109.8 | 47.5 | 146.3 | 153.9 |
| 6 | 32.8 | 142.0 | 146.3 | 59.7 | 793.1 | 778.7 |
| 7 | 30.6 | 134.2 | 0 | 64.5 | 378.8 | 0.0 |
| 8 | 21.2 | 88.1 | 92.4 | 53.3 | 224.6 | 1045.4 |

The average of mooring tension is obtained from dynamic analysis in the time domain (Table 10).

Table 10. Mean Tension

| Mooring Line | Mean Tension (kN) | | | | | |
|---|---|---|---|---|---|---|
| | Experimental Scenario | | | Numerical Scenario | | |
| | I | II | III | I | II | III |
| 1 | 270.4 | 372.7 | 411.8 | 221.9 | 363.7 | 322.7 |
| 2 | 299.7 | 475.1 | 559.3 | 222.9 | 372.5 | 376.9 |
| 3 | 331.0 | 483.7 | 542.8 | 185.1 | 282.5 | 265.2 |
| 4 | 274.6 | 353.1 | 336.0 | 197.7 | 296.1 | 255.7 |
| 5 | 324.0 | 466.0 | 537.1 | 348.9 | 607.2 | 587.2 |
| 6 | 373.7 | 565.6 | 663.9 | 441.6 | 1741.5 | 1804.6 |
| 7 | 367.2 | 564.7 | 0 | 365.4 | 928.1 | 0.0 |
| 8 | 315.0 | 450.1 | 863.9 | 328.7 | 752.5 | 2113.3 |

## 4.3 Maximum Mooring Tension

The maximum mooring tension is the sum of the average tension, the significant low-frequency tension and the maximum wave frequency tension (equation 2). After finding the tension component as in Table 8, Table 9, and Table 10, the maximum mooring rope tension was found as shown in Table 11.

Table 11. Maximum Tension

| Mooring Line | Max Tension (kN) | | | | | |
|---|---|---|---|---|---|---|
| | Experimental Scenario | | | Numerical Scenario | | |
| | I | II | III | I | II | III |
| 1 | 270.4 | 372.7 | 411.8 | 221.9 | 363.7 | 322.7 |
| 2 | 299.7 | 475.1 | 559.3 | 222.9 | 372.5 | 376.9 |
| 3 | 331.0 | 483.7 | 542.8 | 185.1 | 282.5 | 265.2 |
| 4 | 274.6 | 353.1 | 336.0 | 197.7 | 296.1 | 255.7 |
| 5 | 324.0 | 466.0 | 537.1 | 348.9 | 607.2 | 587.2 |
| 6 | **373.7** | **565.6** | 663.9 | **441.6** | **1741.5** | 1804.6 |
| 7 | 367.2 | 564.7 | 0 | 365.4 | 928.1 | 0.0 |
| 8 | 315.0 | 450.1 | **863.9** | 328.7 | 752.5 | **2113.3** |

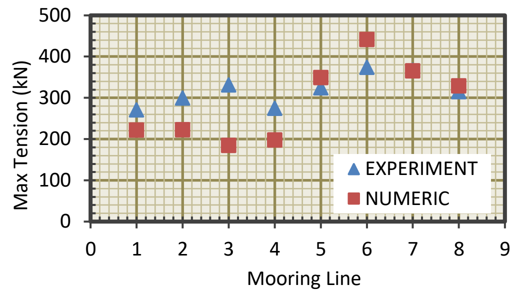



Figure 12. Maximum Tension Scenario I

In scenario 1, the maximum tension of mooring line with experimental and numerical methods occurs in the same mooring line, namely the 6$^{th}$ with a value of 373.7 kN and 441.6 kN.

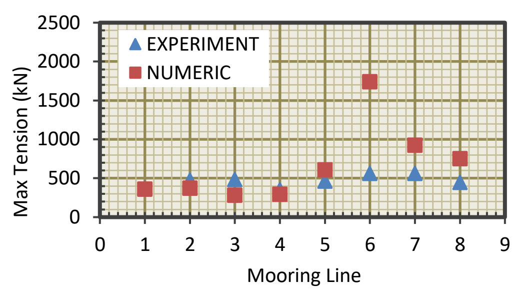



Figure 13. Maximum Tension Scenario II

In scenario 2, the maximum tension of mooring line in the experimental and numerical method occurs in the same mooring line, namely the 6th with a value of 565.6 kN and 1741.5 kN.

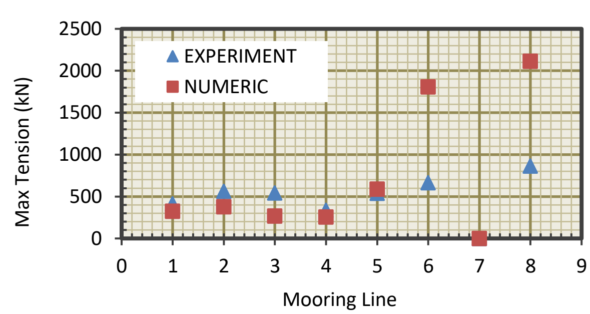



Figure 14. Maximum Tension Scenario III

In scenario 3, the maximum tension of the mooring line in the experimental and numerical method occurs in the same mooring line, namely the 8th with a value of 863.87 kN and 2113.3 kN.

### 4.4. Mooring Safety Factor

The mooring safety factor is a safe limit (permit limit) for the operation of a moored floating building system by observing the maximum tension that occurs in the mooring system. The mooring safety factor value is obtained by comparing the maximum tension to the minimum breaking load value (equation 5).

In this analysis, the load variations are carried out with headings 0°, 45 °, 90 °, 135 °, 180 ° as shown in Figure 15.

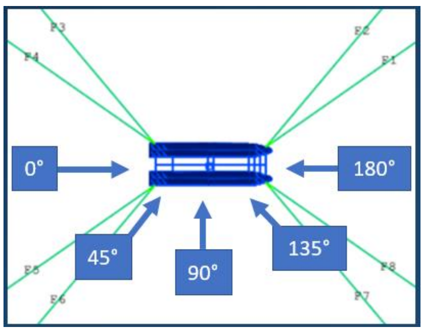



Figure 15. Numerical Analysis Scenario

The results of the mooring safety factor analysis for each variation of are shown in Table 12 and Figure 16.

Table 12. Intact Mooring Safety Factor

| Hs (m) | Maximum Tension | | MBL (kN) | Safety Factor | Criteria Check |
|---|---|---|---|---|---|
| | At Line | Tension (kN) | | | |
| Heading 0° | | | | | |
| 2.5 | 5 | 243.8 | 10215.43 | 41.90 | Pass |
| 3.5 | 5 | 286.7 | | 35.63 | Pass |
| 4.5 | 4 | 355.0 | | 28.78 | Pass |
| 6.37 | 4 | 493.2 | | 20.71 | Pass |
| Heading 45° | | | | | |
| 2.5 | 6 | 295.9 | 10215.43 | 34.52 | Pass |
| 3.5 | 7 | 433.4 | | 23.57 | Pass |
| 4.5 | 6 | 657.8 | | 15.53 | Pass |
| 6.37 | 6 | 1074.6 | | 9.51 | Pass |
| Heading 90° | | | | | |
| 2.5 | 6 | 441.6 | 10215.43 | 23.13 | Pass |
| 3.5 | 6 | 733.2 | | 13.93 | Pass |
| 4.5 | 6 | 1005.6 | | 10.16 | Pass |
| 6.37 | 6 | 1741.5 | | 5.87 | Pass |
| Heading 135° | | | | | |
| 2.5 | 7 | 324.8 | 10215.43 | 31.45 | Pass |
| 3.5 | 7 | 506.5 | | 20.17 | Pass |
| 4.5 | 7 | 828.1 | | 12.34 | Pass |
| 6.37 | 7 | 1325.1 | | 7.71 | Pass |
| Heading 180° | | | | | |
| 2.5 | 8 | 245.3 | 10215.43 | 41.65 | Pass |
| 3.5 | 8 | 276.0 | | 37.01 | Pass |
| 4.5 | 8 | 329.2 | | 31.03 | Pass |
| 6.4 | 8 | 460.8 | | 22.17 | Pass |

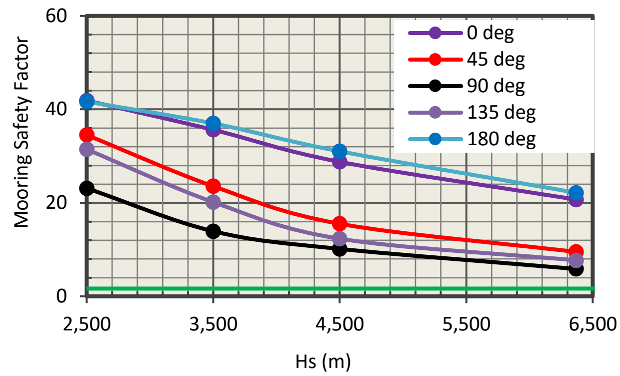



Figure 16. Intact mooring safety factor heading 0°, 45°, 90°, 135°, and 180°

At intact mooring conditions, the smallest mooring safety factor occurs in the heading 90 °. It was found that the largest significant wave height that meets the criteria for mooring safety factor is 6.37 m with a mooring safety factor value of 5.87. This value meets the criteria for mooring safety factor API RP 2SK (≥ 1.67)

The results of mooring safety factor analysis for damaged mooring line condition in wave headings 90 ° are shown in Table 13 and Figure 17.

Table 13. Damaged Mooring Safety Factor

| Hs (m) | Maximum Tension | | MBL (kN) | Safety Factor | Criteria Check |
|---|---|---|---|---|---|
| | At Line | Tension (kN) | | | |
| 2.5 | 8 | 615.2 | 10215.43 | 16.60 | Pass |
| 3.5 | 8 | 1183.1 | | 8.63 | Pass |
| 4.5 | 8 | 1708.2 | | 5.98 | Pass |
| 6.37 | 8 | 2113.3 | | 4.83 | Pass |

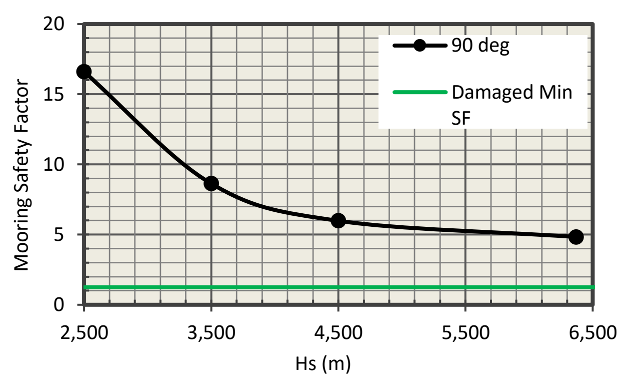



Figure 17. Damaged mooring safety factor heading 0°, 45°, 90°, 135°, and 180°

In damaged mooring line conditions, the smallest mooring safety factor occurs in the direction of wave loading (heading) 90 °. It was found that the largest significant wave height that meets the criteria for the mooring safety factor is 6.37 m with a mooring safety factor value of 4.83. This value meets the criteria for mooring safety factor API RP 2SK (≥ 1.25)

## 5. CONCLUSION

From the analysis of experimental and numerical methods, several conclusions can be drawn as follows

1 In the intact condition, Hs = 2.5 m and Hs = 6.37 m, wave heading at beamseas, the maximum tension of experimental and numerical results occur in the same mooring line, namely the 6th mooring line with a value 373.6 kN and 441.6 kN; 565.61 kN and 1741.5 kN

2 In the damaged condition by breaking the mooring line-7, Hs = 6.37 m, wave heading at beamseas, the maximum tension of experimental, and numerical results occurred in the same mooring line, namely the 8th mooring line with a value of 863.8 kN and 2113.3 kN.

3 The allowed of significant wave height for intact conditions with wave heading 0 ° is 6.37 m with a safety factor value of 20.71, heading 45 ° is 6.37 m with a safety factor value of 9.51, heading 90 ° is 6.37 m with a safety factor value of 5.87, heading 135 ° is 6.37 m with a safety factor value of 7.71, heading 180 ° is 6.37 m with a safety factor value of 22.17. Meanwhile, the damaged heading 90 ° was 6.37 m with the safety factor value of 4.83.

4. With a 5-inch diameter of the mooring line, the intact conditions with 6.37 m significant wave load at 0°, 45°, 90°, 135°, 180° direction meets the API RP 2SK mooring safety factor criteria (≥ 1.67). The damaged condition with 6.37 m significant wave load at 90° direction meets the API RP 2SK mooring safety factor criteria (≥ 1.25).

## 6. ACKNOWLEDGEMENTS

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