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Study on the Material Mechanical Properties of Aquaculture Net Cage

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Abstract. Due to the typhoon impacts, aquaculture net cages may be exposed to the risk of structural failure as a far-reaching aquaculture equipment. In addition, the fatigue problem of key components due to long-term marine alternating loads can not be ignored. The method is developed independently on processing samples of cage for testing its performance parameters, among which the fatigue Wohler curve is $S = -1.022\ln(N) + 22.201$. By adapting the following methods: Mechanical test, Equivalent load finite element simulation and Full field finite element simulation respectively is verified each other, and the error is less than 5%. The key nodes of the stress concentration of the floating frame are mainly the welding point, the mooring point and the edge area of the I-beam frame at both sides. The damage of the cage which caused by tensile and bending loads should be considered at the same time. And the tensile strength 22.12 MPa and the bending strength 30.58 MPa could be taken as the evaluation standard for the elastic to plastic deformation. Structural fracture occurs when the elongation at break exceeds 340.18%. The fatigue of the cage is mainly because the stress is much greater than the fatigue limit 3.38 MPa. The material model test combined with structural mechanics simulation provides the basis for guiding the structural optimization design of the cage.
Keywords. Aquaculture net cage, mechanical properties of material, fatigue life, finite element model.

1. Introduction

High-density polyethylene (HDPE) gravity type net cage has the remarkable advantages of high performance cost ratio, large breeding capacity and so on. In order to reduce the pressure of inshore environment, the net cage should expand to the deep sea, however, the cage system may bend and deform because it may not bear the excessive load of wave environment, especially in the face of super typhoon. And the floating system of net cage is coordinated with the wave, mooring and net loads to do reciprocating motion, so the floating frame may be caused fatigue damage due to vibration load. Especially at present, there is a lack of specification and unified standard in fatigue reliability of net cages.

The structural dynamics method of finite element model (FEM) has a significant advantage in analyzing the risk assessment of net cage system, which can greatly promote the further design and optimization of the cage. Among them, Liu et al. (2017) [1] made nonlinear analysis on the loading response of the cage assembly structure by using the material mechanics test and FEM structural model; Huang (2019) [2] compared and analyzed the test results of mooring force, heave, pitching and rolling of offshore fish farm under different conditions; Nguyena (2019) [3] evaluated the safety factors of different specifications of aquaculture fish farm in extreme storm environment. Moreover, Huang et al. (2016) [4] employed FEM numerical model to study wave dynamic response of net cage floating frame; in addition, Dracha et al. (2016) [5] adopted the FEM method to simulate the key structures such as assembly, welding and I-beam frame of a new type of net cage floating frame. The use of FEM Structural Mechanics Method can effectively study the failure of key nodes of the floating frame, and the plastic yield simulation of the extreme loads of the cage based on the structural analysis has attracted more and more attention from domestic and foreign experts.

The net cage system operation is subjected to the long-term impact of wave dynamic buffering forces, and the structural fatigue under the action of alternating stress in high amplitude and high frequency during the typhoon period needs to be evaluated and calibrated. The vibration response of net cage structure under the periodic action of wave force can be equivalent to the time-domain or frequency-domain static analysis. In related references, Liu et al. (2019) [6] developed FEM vibration models of different cage structures to evaluate the dynamic fatigue response of the floating structure. Hou et al. (2019) [7] predicted the damage distribution of the net cage grid mooring system in different annual fatigue states; Bai et al. (2018) [8] used FEM dynamic model to carry out stress analysis of net cage floating pipe to calculate the fatigue life based on probabilistic analysis of random wave forces; Djebli et al. (2016) [9] determined the fatigue strength of HDPE ∅100 pipe under cyclic loadings through Material Mechanics Tests and built the cumulative fatigue damage-cycle number (D-N) curve derived from decreasing stiffness; Hou et al. (2017) [10] analyzed the fatigue reliability of the net cage mooring time; what is more, Huang et al. (2018) [11] proposed a scientific and technological measure which can effectively enhance the safety of the net cage structure. In conclusion, studies have shown that failures of structural nodes and material damage accumulation all cause the reliability decrease of the cage, and further research should be continued to support the structural safety design for the long-term work.

To sum up, the research about the material and structural mechanic properties of the cage are much important in the domestic and foreign reports, however, the research on the judgment standard of the failure performance of the key structure of the cage is still insufficient, and the specific research on the nonlinear failure and fatigue characteristics of the cage is still needed. Focusing on the above problems, this paper involves the material mechanic tests of tensile, bending and vibration loading modes and the finite element structural simulation of the evaluation to the plastic failure and fatigue of net cage.

2. Correlative Calculation of Mechanical Performance Parameters of Net Cage

2.1. Calculation of Mechanical Parameters of Net Cage Material

(1) The equation for calculating the elastic modulus of 0.05% -0.25% string is

$$E_t = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{1}$$

E_t is the tensile modulus in the equation, the unit is MPa; σ_1 is the stress measured when strain ε_1= 0.0005, the unit is MPa; σ_2 is the stress measured when strain ε_2 = 0.0025, the unit is MPa.

(2) Elongation at break is calculated by the following equation:

$$\varepsilon = (L\text{-}L_0)/L_0\times 100\% \tag{2}$$

In the equation, ε is the elongation at break, %; L is the length between the marked lines at break, the unit is mm; L_0 is the original length between the marked lines, the unit is mm.

(3) Non-linear static analysis equilibrium equation of high density polyethylene (HDPE) net cage

$$[K(x)]\{x\}=\{F(t)\} \tag{3}$$

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$\{x\}$ is the displacement vector in the equation; $\{F(t)\}$ is the force vector; $[K(x)]$ is the stiffness coefficient matrix, which depends on the displacement $\{x\}$, and it is not constant.

(4) The kinetic equation of net cage floating structure

$$F(t) = M\ddot{u} + C\dot{u} + Ku \tag{4}$$

$F(t)$ in the kinetic equation is the load acting on the cage; M, C, K represent mass, damping, and stiffness matrices, respectively; u, $\dot{u}$, $\ddot{u}$ is the displacement, velocity, and acceleration vectors of the floating structure nodes, respectively.

(5) The fourth strength design theory adopts Von-Mises Yield Criterion, as follows:

$$\sigma_0 = \sqrt{\frac{1}{2}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2]} \tag{5}$$

In the equation, σ_x, σ_y and σ_z are the principal stress in three coordinate axes, respectively; σ_0 is the equivalent stress.

(6) The calculation equation for the bending strength of the net cage material is

$$\sigma_f = \frac{3PL}{2bh^2} \tag{6}$$

In the equation, σ_f is the bending strength, and the unit is MPa; P is the maximum load on the sample, and the unit is N; L is the span, and the unit is mm; b is the width of the sample, and the unit is mm; h is the thickness of the sample, and the unit is mm.

(7) The calculation equation of bending modulus of net cage material is

$$E_f = \frac{L^3 \Delta P}{4bh^3 \Delta f} \times 10^{-3} \tag{7}$$

E_f is the bending modulus in the equation, and the unit is GPa; $\triangle P$ is the load at the linear stage on the deflection curve, and the unit is N; $\triangle f$ is the deflection corresponding to the load, which refers to the distance that the center of the sample's span deviates from the original position during the bending process, and the unit is mm; the relation of the deflection with strain ε and curvature κ is linear, and a is the coefficient, as follows

$$\triangle f = \varepsilon L^3/6h = a\kappa \tag{8}$$

(8) The calculation equation for the curvature of the net cage pipe is

$$R = \triangle f/L \times 100\% \tag{9}$$

2.2. Finite Element Plastic Yield Model of Net Cage Structure

The grid units are allocated according to the structure size and analysis type of the cage model. The tetrahedral grid division method and tetrahedral grid division method are mainly used. The number of nodes in C60 and type 6-3 cage [4] is more than 2×10^5, and the number of cells is over 10^5. Each node has 6 degrees of freedom, that is, translation and rotation in the x, y, and z directions; the finite element contact types of are bonded, no separation and frictionless.

(9) Newton-raphson equation balance iteration method is used to solve the nonlinear problem of FEM structure of net cage. The load is divided into several increments, and each increment determines a balance condition. At the end of each load increment, the balance iteration drives the solution back to the balance state.

$$[K_T]\{\triangle u\} = \{F_a\} - \{F_r\} \tag{10}$$

In the equation, $[K_T]$ is tangent stiffness matrix; $\{\triangle u\}$ is the displacement increment; $\{F_a\}$ is the applied load vector; $\{F_r\}$ is the internal force vector.

2.3. Fatigue Mechanics Calculation of Finite Element Model of Net Cage

(10) The key loading parameters of the residual fatigue strength test including the stress level and stress ratio of cyclic loading N times. The test waveform is sine wave, which belongs to the tensile fluctuating stress. And the loading frequency is f=10 Hz. The equal proportion loading method is adopted, and the fatigue force is "0-F". The characteristic of sinusoidal fatigue load is

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

$$\sigma_{alt} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{11}$$

In the equation, σ_m is the stress level; σ_{alt} is the stress amplitude; σ_{max} is the maximum stress; σ_{min} is the minimum stress; the stress ratio $R=F_{min}/F_{max}=\sigma_{min}/\sigma_{max}=0$.

(11) The finite life design of HDPE net cage is based on Palmgren-Miner Linear Fatigue Cumulative Damage Theory

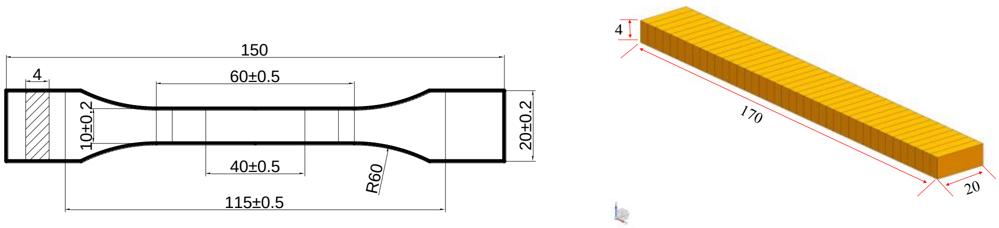
$$\sum_{i=1}^{n} D_i = \sum_{\sigma_i} \frac{n_i}{N_i} \le 1 \tag{12}$$

In the equation, n_i is the number of stress cycles acting on the i-th level stress level σ_i; N_i is the fatigue life when the stress level reaches failure, and the net cage will be damaged when the cumulative damage D_i=1.

3. Mechanical Test and Structural Mechanical Parameters of Net Cage Material

3.1. Preparation of Tensile, Bending and Welded Specimens for Cage Pipe of Net Cage

With reference to GB/T 15558.1-2015 and ISO 2818-1994, the national standard sample of floating pipe is processed by ourselves, and the sample preparation process is (1) a CNC saw is used to longitudinally cut ∅110 mm HDPE pipe into the length of 300mm short tube blank, and cut into rectangular bars with a width of 30 mm; (2) the two sides of the dumbbell-shaped samples are high-speed copy milled by the machining center, and then the front and back sides of the samples are planar milled to a specified thickness, equipped with a liquid coolant to avoid heat accumulation in the sample at the same time; (3) the utility knife is used to repair the corner burrs and the sample is rub by sandpaper until the surface smoothness level meets the requirements, then inspects the sample's grinding surface, edges and cutting areas, and finally the cutting surface is flat and free of cracks, scratches, and machining damage. Tensile and bending specimens are shown in figures 1a and 1b.



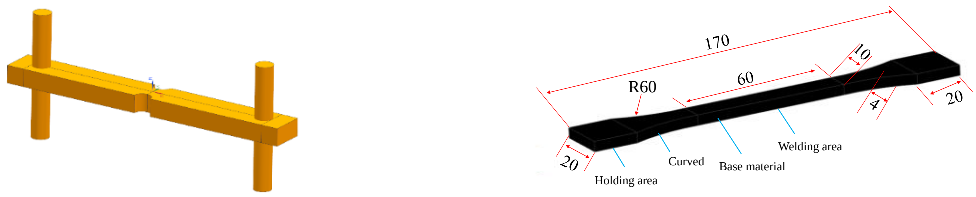
(a) Size of dumbbell-shaped tensile specimen (b) Size of rectangle-shaped bending specimen

Figure 1. Sample structural diagram of cage.

HDPE pipe is considered as isotropic material. The hot-melt welding of pipe is referred to GB/T 20674.1-2006, and the time and pressure used at each stage depends on the pipe specifications. The standard size ratio SDR=d_n/e_n=11 (d_n is the nominal outer diameter of the pipe and e_n is the nominal wall thickness). The welding parameters of ∅100 pipes are shown in table 1. According to GB/T 19810-2005, the optimized design of the welding specimen is shown in figure 2.

Table 1. Process parameters of hot-melt welding of ⌀110 cage.

Pipe diameter (mm)	Wall thickness (mm)	Preheat, heat absorption and welding pressure (MPa)	Preheat and heat absorption temperature (°C)	Heat absorption time (s)	Switch time (s)	Welding time (s)
110	10	0.2	220	160	6	720



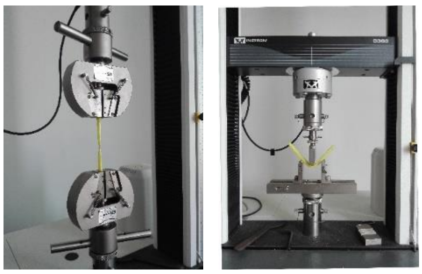
(a) Optimized welding sample (b) Dumbbell-shaped welding specimen

Figure 2. Tensile test sample of welding and optimized form of cage.

3.2. Tension and Bending Test Process of Net Cage Samples

The key indicators of the net cage samples are tested by referring to the GB/T 8804.2-88 and GB/T 1040.1-2006. The preload control rate is 2 mm/min, and then the tensile rate is switched to 50 mm/min when the measurement stress reaches 0.2 MPa. The dumbbell-shaped tensile specimen is shown in figure 3a. The criterion of testing end is 40% decrease of the loading rate, and the sample test is repeated 10 times or more for each group to obtain the test result.

Bending test was referred to ASTM D790-03, GB/T 9341-2008 and QB/T 2803-2006. Under the specified sample thickness, the bending angle and extrusion distance of the sample are measured to evaluate the bending performance of the net cage sample (equations (6)-(9)). What is more, the radius of the indenter R_1 and the support R_2 are both 5 mm. The bending load rate is 4 mm/min, and the span of the positioning rectangle-shaped bending specimen is $L = 15$, $h = 60$ mm. The maximum stress during the process of bending deformation to fracture of the sample is as the bending strength of the net cage. The bending test process of the rectangular-shaped sample is shown in figure 3b.



(a) Tensile test (b) Bending test

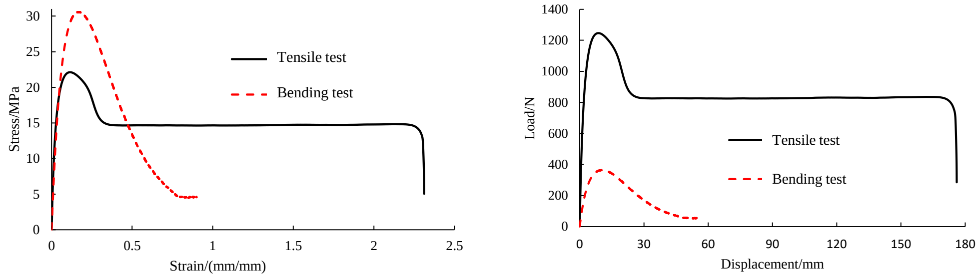
Figure 3. Experimental process of tensile and bending test of cage.

3.3. Operating Condition Model of HDPE Net Cage Structure

The net cage is one kind assemble and welding structure of HDPE pipe coils (figure 4). The structural parameters are seen in table 2.

Table 2. FEM structural properties of HDPE net cage.

	Length (m)	Width (m)	Height (m)	Volume (m^3)	Mass (kg)
Type C60	20.8	20.8	1.4	3.18	3022.5
Type 6-3	22.3	19.4	1.4	2.16	2050.7



(a) Stress-strain curve (b) Load-displacement curve

Figure 4. Mechanical testing results of HDPE specimen under tensile and bending loads.

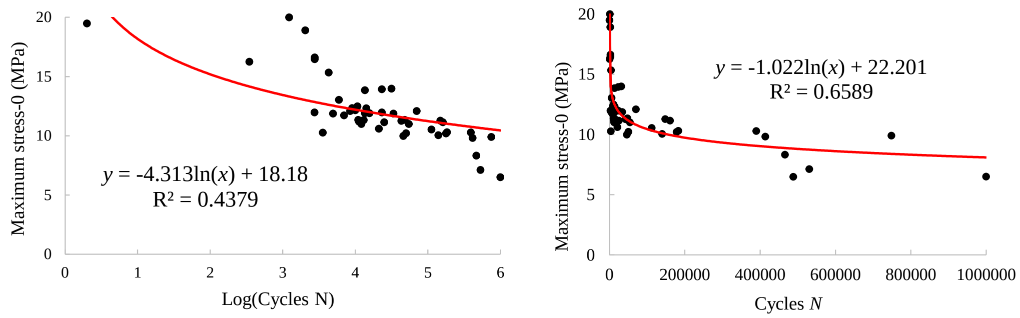
Table 3. Mechanical properties of tensile and bending tests of HDPE floating specimen.

Specimen	Sectional area (mm^2)	Yield stress (MPa)	Modulus (MPa)	Yield load (N)	Deformation (mm)	Fracture location
Tensile	56.41	22.12	692.69	1246.50	176.07	Middle and upside
Tensile (welding)	151.00	11.33	821.24	1710.12	61.19	Welding joint
Bending	133.35	30.58	513.71	363.47	56.08	Middle

From table 3, equations (2) and (9), the elongation at break of HDPE net cage is (176.07-40)/40×100%=340.18%, and the bending degree is 93.47%.

3.4. Fatigue Test and Stress-Period Wohler Fitting Curve of Net Cage

The net cage material adopted the Instron 8801 fatigue tester to conduct the low-cycle and high-cycle fatigue reliability tests. Under the circumstance of 50% failure probability, each stress level (equation (12)) is tested on more than 10 samples to carry out the research on flexural fatigue resistance, and the selected fatigue stress level is 6 non-equidistant magnitudes from 1 to 10^6 times. The function distribution is shown in figure 5.

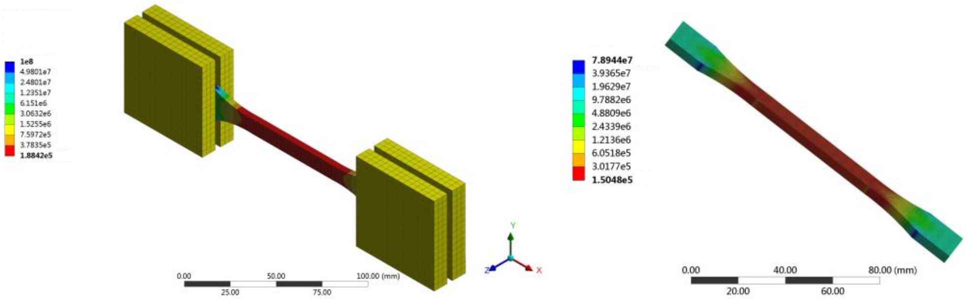


(a) *S*-Log(*N*) (b) *S*-*N*

Figure 5. The fitting curve of stress amplitude vs cycle numbers (Wohler curve) of cage (Wohler curve: *S*-Stress amplitude, *N*-Cycle numbers to failure).

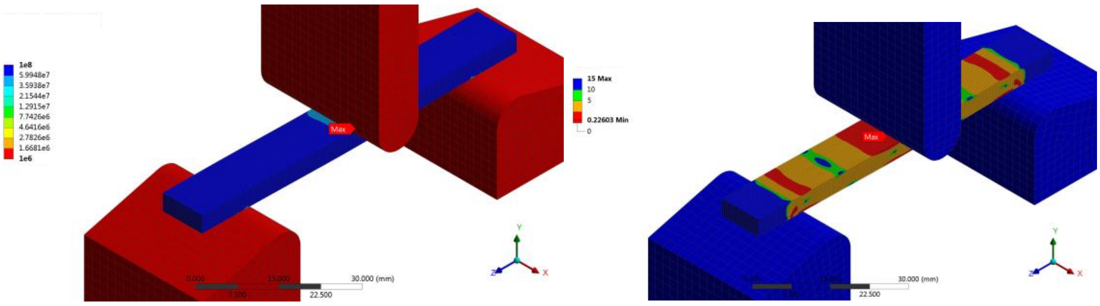
3.5. FEM Analysis Results of Dumbbell-Shaped Tensile Specimen and Rectangle-Shaped Bending Specimen

The 1:1 3-D tensile and bending model corresponding to the test situation is established, as shown in figures 6, 7 and table 4.



(a) Life of full scene simulation in 0-1 kN (b) Life of specimen in 0-1 kN

Figure 6. FEM fatigue results of floating specimen obtained by tensile load 0-1 kN.



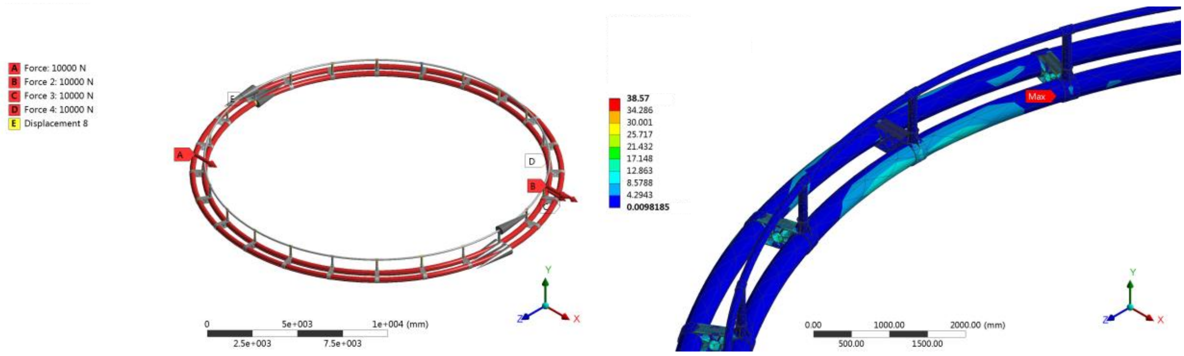
(a) Bending life (b) Safety factor

Figure 7. FEM fatigue results of cage floating specimen obtained by bending load 0-20 N.

According to the test and finite element simulation, the minimum life of 0-1 kN dumbbell-shaped tensile test is 1.436×10^5, the finite element elastic tensile life of pure dumbbell-shaped is 1.505×10^5, and that of full scene is 1.884×10^5. The finite element full scene elastic bending life of 0-20N load is 10^6, and the maximum damage zone is the contact support area of both ends and the center of the rectangular-shaped specimen.

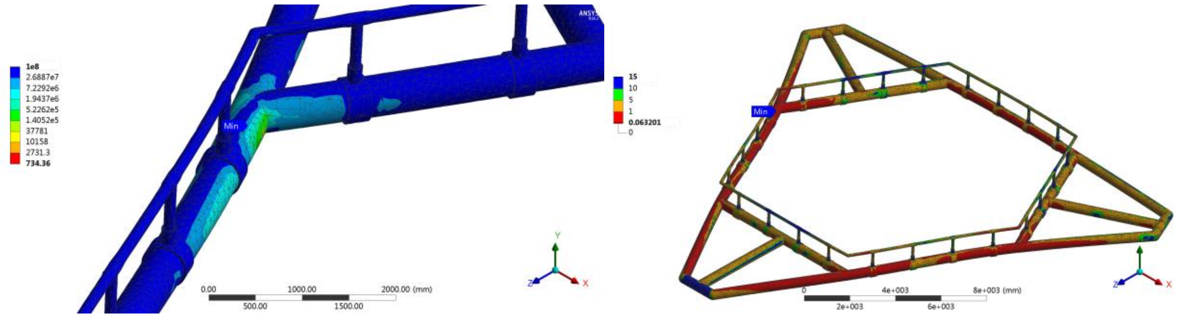
3.6. Finite Element Structural Models of C60 and Type 6-3 Net Cage

By applying alternating load and mooring constraint, fatigue risk of cage under long-term wave load in elastic stage is evaluated. And the results of the finite element analysis are shown in figures 8, 9 and table 5.



(a) SPM and uniform load 40kN (b) Maximum stress points

Figure 8. FEM results of Single Point Mooring (SPM) and uniform load 40 kN of C60 cage.



(a) Minimum life points (b) Safety factor diagram

Figure 9. FEM results of SPM and uniform load 40kN of type 6-3 cage.

According to figures 7 and 9, the minimum fatigue life of one single point restraint and uniform load 40kN of type 6-3 net cage is 734 < 10^3 cycles, which is the same as the zone with the minimum safety factor and the maximum stress, it's the intersection zone of the inner hexagon and the outer triangle that far away from the mooring load.

4. Discussion

4.1. Mechanical Properties Analysis of Tension, Bending and Fatigue Tests of Net Cage

The yield fracture rule of HDPE cage sample is shown in figure 4 and table 3, and the mechanical properties of materials are consistent with the research scope of other scholars [9]. When the tensile rate is at 10mm/min, the welding material of the sample is completely plastically stretched; when the tensile rate is at 50mm/min, the elongation at break of the weld is significantly reduced. The elongation at break and yield strength of the welded floating specimens are smaller than the base material, but the elastic modulus is larger, indicating that the strength, stiffness and toughness of the welded structure are reduced, which is a risk area for cage.

From figure 5, S - Log$N$ is S = -4.313ln(N)+18.18; S - N is S = -1.022ln(N)+22.201. Comparing with the research result S = -1.85ln(N)+35.6 of Khelif et al. (2008) [12], the fatigue life of this study is relatively smaller when the fatigue stress levels are same. When the fatigue life n ≥ 10^6, the maximum working stress σ_{max} should not exceed the allowable stress [σ_6], that is, $\sigma_{max} \leq [\sigma_6]$ = 8.08 MPa; the stress level corresponding to the extension of the *Wohler* curve to the horizontal straight line is the fatigue limit, that is, the times of cycle is 10^8, [σ_8]=3.38 MPa. It is considered that the HDPE net cage will be subjected to fatigue damage when the stress level is higher than 3.38 MPa.

4.2. Finite Element Simulation Analysis of Tension, Bending and Fatigue of Net Cage Samples

According to table 4, the stress results of dumbbell-shaped and full-scene tensile models under 100N load are compared and verified, and the error is (2.695-2.69)/2.695×100%=0.19% <1%. When the load is 800 N, the difference of elastic and plastic model stresses in the full scene of the cage sample is (21.55-20.46)/21.55×100% = 5.06% > 0. Under the condition of same load, the stress value of the elastic model is bigger than that of the plastic model, that is to say, using the finite element elastic equation to calculate the cage model can ensure the safety requirements [6]. The finite element tensile simulation result shows that the stress is maximized in the area near the center of the sample and necking occurs. There is no shoulder fracture and plastic deformation extending to the entire shoulder of the dumbbell-shaped sample, which is consistent with the test situation; the equivalent load finite element model, full scene finite element model and mechanical test are used to verify the accuracy and validity of each other, which have met the engineering accuracy requirements. Through the amplitudes of 0-1 kN and a frequency of 10 Hz tensile vibration fatigue tests, the fatigue life of the HDPE dumbbell-shaped specimen is obtained, which is 1.436×10^5. And the finite element simulation lives are 1.505×$10^5$and 1.884×10^5, respectively, which are both at the 10^5 life stage. As shown in figure 6, the damage of 0-1000

N is extended to the middle area of the inside arc transition of the dumbbell-shaped sample, indicating that the sample has been damaged; the minimum finite element fatigue life of the load 0-100 N is 5.319×10^7, and the damage area is small and meets the requirements of operation durability.

Table 4. FEM simulation results under tensile and bending loads of cage floating specimen.

FEM specimen model	Load (N)	Displacement (mm)	Stress (MPa)	Strain (mm/mm)
Tensile/elastic in dumbbell-shape	100	0.24	2.690	0.002445
Tensile/elastic in full scene	100	0.25	2.695	0.002449
Tensile/elastic in full scene	800	7.94	21.550	0.019593
Tensile/plastic in full scene	800	7.54	20.460	0.018599
Tensile/plastic in full scene	1000	17.70	22.120	0.020109
Bending/elastic in rectangle-shape	20	6.29	12.376	0.011250
Bending/elastic in full scene	20	6.43	13.465	0.013000

According to table 4, the stresses of full scene elastic bending model and pure long strip bending model are 12.376 MPa and 13.465 MPa, respectively, with the error of (13.465-12.376)/13.465×100% = 8.09% < 10%. The destruction phenomenon of finite element equivalent load model, finite element full scene model and the loading failure mode obtained from the material mechanics test are the same, which showed that it is reliable to use the floating structure model to analyze the tensile and bending responses of the equivalent wave and mooring loadings. The fatigue life and damage distribution of the cage specimens are calculated, and the low cycle and high cycle fatigue failure conditions of the net cage structure in long-term operation are predicted. When the bending stress of 0-134.65 MPa is bigger than the tensile stress of 0-131.29 MPa, the bending life of 10^6 (figure 7a) is longer than the tensile life of 1.884×10^5, which indicated that the vibration fatigue damage of the net cage under tensile load is greater, and the main reason is that the tensile strength is less than the bending strength (equation (6)). The flexural modulus of 513.71 MPa (equation (7)) is less than the elastic modulus of 692.69 MPa, and the bending degree of 93.47% is smaller than the elongation at break of 340.18%, that is, under the condition of bending load, the static load damage is greater. Therefore, the the failures of tensile and bending operations of the net cage should be considered at the same time.

4.3. Nonlinear Behavior Failure Analysis of HDPE Net Cage Finite Element Structure Model

The finite element structure model of the net cage is based on the load and restraint method of the mooring and net clothing applied to the cage under the wave conditions, and the stress response spectrum is obtained by applying to the corresponding nodes of the structure (figures 8 and 9), which clarifies the mechanical response characteristics and inherent laws of the net cage structure. Based on equations (9) to (10), the nonlinear mechanical performance data of the circular and type 6-3 of net cage structures are compared and analyzed, and by combining with the material mechanics tests, the structure of the net cage is optimized to make the stress distribution more reasonable. From figure 9, the minimum safety factor of the type 6-3 floating frame is distributed in the area connecting the inner hexagon and the outer triangle far from the mooring point, and this area has a sharp change in shape and uneven stress distribution. The nonlinear behavior of the float finite element model is mainly due to the plastic deformation of the key nodes geometry (equation (3)), and the deformation of the cage should be less than 953.58 mm (table 5).

In the elastic failure stage, taking the tensile strength of 22.12 MPa and the bending strength of 30.58 MPa as the critical standards. In the plastic failure stage, after the inner wall of the HDPE pipe reaches yielding, it will not cause damage immediately, and when the plastic zone continuously expands to the outer surface and the elongation at break exceeds 340.18%, the structural fracture occurs after the overall yielding. From figures 8 and 9, tables 3 and 5, the maximum stress mainly appears at the welding point, mooring point and the edge area of the I-beam on both sides. When the uniform load is 40 kN, the equivalent stresses of the single-point mooring and the 8-point mooring of the C60 net cage model are 38.57 MPa and 3.62 MPa, respectively. The 8-point mooring stress is about 1/10 of the single-point mooring stress. According to equation (5) and the allowable stress method analysis, increasing the mooring points can significantly reduce the ductile fracture behavior of net cages.

Table 5. FEM structural analysis of net cage.

FEM of float	Mooring points	Uniform load (kN)	Displacement (mm)	Stress (MPa)	Strain (mm/mm)
Type 6-3	1	40	953.58	24.078	0.022060
C60	1	40	666.00	38.570	0.035135
C60	8	40	10.23	3.620	0.003133
C60	8	800	72.34	24.610	0.022652

4.4. Fatigue Failure Analysis of HDPE Net Cage Structure Model Based on Wohler Curve

Due to the wave effect, the cage floating frame, the anchorage and the net clothing are in constant contact with each other or undergo sudden changes in stiffness, which causes the conditions to change continuously (equation (5)). The maximum stress of the single-point mooring load 40 kN of the C60 net cage is 38.57 MPa, which is bigger than that of the type 6-3 net cage's 24.08 MPa. Under this load condition, the theoretical stress concentration factor $K_T = \sigma_{\max}/\sigma_c$ (σ_c is the standard stress value) of the type 6-3 net cage structure is smaller than the circular type, that is, when in the form of single-point mooring, the circular cage can refer to the optimal design of the type 6-3 structure. According to equation (4), figures 8 and 9, the circular cage mainly bears bending load and presents elliptical reciprocating vibrations [13]. The curved circular cage is suffered alternating compression force at the outside and transient tension at the inside; when type 6-3 net cage is in the single-point mooring and with a uniform load, it's deformed in both tensile and bending types.

From figure 9, when the type 6-3 net cage is in the single-point mooring and with the uniform load of 40 kN, the minimum fatigue life is $N = 734 < 10^3$ cycles, which is mainly including the fatigue crack formation life N_c, according to the test, approximately 90% of the fatigue life; and the expansion life of main crack to failure is N_g. The local gaps of the circular and type 6-3 net cage structures are in long-term elastic deformation (figure 4), and the failure mode is that fatigue damage is triggered mainly through repeated application of stress. Under the condition of long-term wave loads, the mooring, welding, and I-beam edge areas of the net cage are the key parts of fatigue damage. By reducing the SDR coefficient of the key areas of the float and increasing the local areas of stress concentration (figures 8 and 9), the safety, reliability and service life of the net cage can be improved effectively under wave loads.

5. Conclusion

Mechanical tests and finite element (FEM) analysis of the net cage float under nonlinear static loads and vibration fatigue processes are conducted in the article. The research results showed that

(1) The fatigue Wohler curve of HDPE net cage is S = -1.022ln(N)+22.201. Fatigue damage occurs when the stress concentration is greater than the fatigue limit of 3.38 MPa.

(2) Mechanical test, FEM sample model, and full scene FEM model are adopted to verify each other, and can meet the requirements of engineering accuracy.

(3) Comparing with the tensile stress mode, the bending stress has greater damage to the net cage float in static loading type, and smaller damage in vibration fatigue type. In the elastic failure stage, the tensile strength 22.12 MPa and the bending strength 30.58 MPa are used as the elastic-plastic deformation evaluation criteria, and the elongation at break is 340.18%.

(4) The minimum life mainly occurs in the mooring point, welding point and the edge areas of I-beam on both sides. By means of increasing mooring points and reducing SDR coefficients in critical areas, the limit bearing capacity and fatigue reliability of net cage float under long-term wave vibration environments can be improved.

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