



Article Fatigue Characteristic of Designed T-Type Specimen under Two-Step Repeating Variable Amplitude Load with Low-Amplitude Load below the Fatigue Limit

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Abstract: In order to investigate the non-linear fatigue cumulative damage of joints in ocean structural parts, one type of low carbon steel Q345D was employed to prepare designed T-type specimens, and a series of fatigue experiments were carried out on the specimens under two-step repeating variable amplitude loading condition. The chosen high cyclic loads were larger than the constant amplitude fatigue limit (CAFL) and the chosen low cyclic loads were below the CAFL. Firstly, the S-N curve of designed T-type specimen was obtained via different constant amplitude fatigue tests. Then, a series of two-step repeating variable load were carried out on designed T-type specimens with the aim of calculating the cumulative damage of specimen under the variable fatigue load. The discussions about non-linear fatigue cumulative damage of designed T-type specimens and the interaction effect between the high and low amplitude loadings on the fatigue life were carried out, and some meaningful conclusions were obtained according to the series of fatigue tests. The results show that fatigue cumulative damage of designed T-type specimens calculated based on Miner's rule ranges from 0.513 to 1.756. Under the same cycle ratio, the cumulative damage increases with the increase of high cyclic stress, and at the same stress ratio, the cumulative damage increases linearly with the increase of cycle ratio. Based on the non-linear damage evaluation method, it is found that the load interaction effect between high and low stress loads exhibits different damage or strengthening effects with the change of stress ratio and cycle ratio.

Keywords: variable amplitude loading; cyclic load below fatigue limit; low carbon steel; load interaction; strengthening effect

1. Introduction

Fatigue failure is a common phenomenon in steel structures of the ships and ocean assemblies, which are always subjected to cyclic loading during service [1,2]. Fatigue failure always appears at the local region of mechanical parts or components. In most cases, the cyclic loads applied on the structure of ship and ocean engineering are not constant but variable. Prediction of the fatigue life of structures under variable cyclic loads accurately is crucial for the engineers in the field of ocean and structural engineering, and that requires comprehensive understanding the damage mechanism of structures under the different types of variable fatigue load blocks.

Fatigue damage in metals is a process of irreversible accumulation, which is manifested by progressive internal deterioration of material due to nucleation and growth of micro-cracks, debonding, voids, and so on [3,4]. In general, fatigue failure contains three stages: crack initiation, crack propagation and final catastrophic failure. The difference



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). between high cycle fatigue and low cycle fatigue lies in the percentage of the total life spent in each of three stages. As to the high cycle fatigue, much of the fatigue life is spent in the crack initiation stage [4]. Crack initiation is a highly random event which is strongly affected by the initial state of material properties and microstructural defects [5,6].

In order to predict the fatigue life of metallic components, it is necessary to find a reasonable method to calculate the fatigue damage accumulation in variable amplitude cyclic loads. For a long time, most of design engineers in industry always use Palmgren–Miner law to estimate the fatigue lives of metallic components due to relatively accurate and easy operation of this method. The Palmgren–Miner law is a linear damage rule (LDR). The value of cumulative damage (*D*) can be calculated by the Equation (1):

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i} = \sum r_i \tag{1}$$

where n_i is the number of cycles at a given stress amplitude load, N_i is the cycles to failure at the same stress amplitude load. Miner's rule suggests that any structure with D < 1.0 during a fatigue test is safe.

The assumption in Miner's rule is that the fatigue damage due to each of a particular cyclic load in a fatigue test with variable amplitude (VA) loads is exactly the same as that in the fatigue test with a constant amplitude (CA) load [7]. However, there are a large number of previous works [8–14] indicating that VA load fatigue tests induce larger fatigue damage than the calculated results by the Miner's law, which leads to non-conservation of Miner's rule in actual VA load fatigue life predictions (i.e., fatigue failure when D < 1.0). The main deficiencies of LDR are no consideration of the effect of load sequence, the effect of the damage of low amplitude load below fatigue limit and the interaction effect between the high and low amplitude loadings on the fatigue life prediction. Therefore, the fatigue life predictions are unsafe in some cases [16]. Many researchers tried to modify the form of Miner's rule with the aim of predicting fatigue life precisely. Marco and Starkey [17] proposed a non-linear load-dependent damage rule firstly as follows:

$$D = \sum r_i^{x_i} \tag{2}$$

where x_i is a coefficient depending on the *i*th load. The main novelty of this rule is that the effects of different loading sequences are taken into account in calculation. However, the actual predicted result is usually unsatisfactory, and the experimental results showed that the good agreement only occurred in some cases and some materials [18].

Another approach is making use of the concept of fatigue limit reduction to measure the damage accumulation, when a multi-level load is applied and many rules based on the S-N curve modification have been developed [19]. For all these theories, the original curve is replaced by modified curves. Although these approaches are non-linear damage rules, few of these approaches take into account the load interaction effect.

There are some different methods of treating variable cyclic loading spectra containing the constant amplitude fatigue limit (CAFL) and calculating by the Miner's law [20,21]. The most widely used assumption is that the S-N curve extrapolated beyond the load cycles at 10^7 with a relatively flat slope [22–24], and the damage accumulation rule is still Miner' rule. However, a large number of experiments [9,25–31] show that in fact the actual fatigue damage is larger than in the assumption method. For example, it was reported [12] that the use of a 2-slope S-N curve with the slope change at a stress range above 10.1 N/mm² (corresponding to about 5.5×10^8 cycles) was potentially unsafe, particularly for loading spectra containing a large number of small cyclic stresses. Moreover, this was especially true for fatigue life of components under the tensile load.

In ship and ocean engineering, there are many joints in structural parts, such as the intersection between longitudinal and transverse bulkhead [32–34] which is one of the typical ship structures and is prone to fatigue failure during ship voyages. There are

many techniques to perform structural health monitoring to guarantee the structural parts' safety during service. In the process of structural health monitoring, it is important to accurately capture or predict the deformation of structures. The stresses and displacements of the structural components in the ships can be calculated by different analytical theories and finite element methods. The Carrera unified formulation (CUF)-based finite element analysis (FEA) model has been validated to accurately simulate the deformation of complex structures by laser-based experiments [35]. Nondestructive testing (NDT) are usually employed to assess structural health and secure structure integrity. With the measurements of laser tracker and terrestrial laser scanning, an optimized surface model can be established as a high-accuracy NDT metrology tool [36]. To obtain accurate deformed state of a given composite thin-walled structures, the geometric nonlinear effects of the composite structures can be analyzed by the CUF-based FEA model [37]. Meanwhile, with the consideration of geometrical nonlinear relations in beam and shell-like structures, the deformed state of a given structure can be correctly captured by refined theories based on the CUF [38]. Although the developed theoretical methods promote the structural health monitoring of the structural parts, the fatigue experiments are still necessary to improve the service life of structural parts.

There is a special type of ship called river-sea going ship, which repeats voyaging between the inland river and coast sea along a special voyage line, and the loading environment from which the ship suffers, is much like the two-step repeating load block [39]. When the ship voyages on the sea, the loading on the ship by the sea wave is different from the river wave in the inland river. The loading on the ships can be variable whether the ships voyage on the sea or the inland river. Usually, the high loading on the ship by the sea wave is larger than that by the inland river. Here in the paper, the variable loading on the river-sea going ship is approached by the model of two-step repeating variable amplitude load with low-amplitude load below the fatigue limit. Therefore, a study on fatigue characteristic of designed T-type specimen under the two-step repeating amplitude loading block was carried out in this work. The loading block contained high cyclic load and low cyclic load levels. The high cyclic load was above the CAFL and the fatigue life produced by the high cyclic load lied in the high cycle fatigue range, and the low cyclic load was below the CAFL. Firstly, tensile tests were conducted on the designed T-type specimens to get the material mechanical properties. Then a series of fatigue experiments with both the CA loading and the two-step repeating amplitude load block were conducted on designed T-type specimens. Furthermore, as a comparison, Miner's rule was used to calculate the fatigue damage accumulation of designed T-type specimen, under every two-step repeating cyclic load condition. Finally, the nonlinear damage parameter was introduced to evaluate the load interaction effect and some conclusions were drawn.

2. Experimental Setup

All the fatigue experiments were carried out via an MTS 322 250 kN Dynamic Fatigue Testing System at the Ship Structure Laboratory of Wuhan University of Technology (Wuhan, China). Figure 1a shows the overall layout of the experiment. The MTS equipment consists of a servo-hydraulic actuator (1) and controller (2). One end of the fatigue specimen was fixed in the platform (3) and the other end was actuated via the servo-hydraulic actuator (1). Figure 1b shows the clamping state of the specimen in fatigue tests. The fatigue test specimen was installed between the grippers (4). All fatigue tests were conducted at room temperature (20 $^{\circ}$ C).



Figure 1. Load frame of the test (**a**), the installation of designed T-type specimen (**b**). A servo-hydraulic actuator (1), a controller (2), the platform (3), grippers (4).

2.1. Material

The material used for the fatigue test was one type of low carbon steel, Q345D steel. Its chemical compositions (in Wt%) were listed in Table 1. In order to obtain the mechanical properties of Q345D steel, tensile tests were conducted on the standard specimen. Figure 2 shows the standard specimen of the tensile test. The tensile tests were conducted in accordance with the published standard [40]. The test results of mechanical properties are shown in Table 2.

Q345D	Element	С	Mn	Si	S	Р	Ni	Cr	Мо	V	Cu	Fe
	Wt%	0.15	1.39	0.28	0.003	0.015	0.01	0.05	0.007	0.004	0.04	Balance

 Table 1. Chemical compositions of Q345D steel.

 Oil
 Oil



Figure 2. The fractured specimen after the tensile test.

Ultimate tensile strength, σ_{UTS} [MPa]	539
Monotonic yield strength, σ_{YS} [MPa]	384
Young's modulus, E [GPa]	206
Poisson's coefficient, v	0.26
elongation, δ [%]	30.5

Table 2. Mechanical properties of Q345D steel.

2.2. Designed T-Type Specimen

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Figure 3 shows the specimen and its dimensions employed in a fatigue test. The thickness in the middle of uniform cross section was 8 mm. The specimen was prepared with the method of wire-electrode cutting to guarantee its size precision. The specimen had a bilateral symmetrical T-type step (labelled as "A" in Figure 3a) which caused highly localized stress concentration. When the test specimen was subjected to cyclic loading, failure occurred at the T-type step ("A" in Figure 3a).



Figure 3. (a) The specimen and its dimensions after a fatigue test; (b) the dimensions of the specimen before a fatigue test.

2.3. Strain Measurement

The strain gauges were placed along the step on the surface of uniform cross section on both sides (shown in Figure 4) to measure the strain value variation and to monitor the crack initiation [41]. The stress concentration factor (SCF) at the T-type step ("A" in Figure 3a) was 1.9 according to the method proposed by Dong [42]. The value of the radius at the crack starting zone was 0.4 mm.



Figure 4. The arrangement of strain gauge on the specimen.

2.4. Fatigue Test

The test program involved both CA and VA loading tests on designed T-type specimens. Figure 5 shows the fatigue experiment setup. Figure 5 is the Microscopy System of KEYENCE which was used to observe the fatigue crack at the step ("A" in Figure 3a). All the fatigue tests were conducted with a frequency of 20 Hz in the force control mode. Loading of sinusoidal type was applied at room temperature. Fatigue tests stopped when the cracks on a specimen were found. Figure 6a shows the fracture surface of designed T-type specimen after fatigue failure. Figure 6b shows the crack initiation zone and the path of crack propagation. As shown in Figure 6b, the crack always initiated at one side of the specimen at the step ("A" in Figure 6b) and propagated in the Y direction on the surface. The crack changed its propagation direction into the Z direction after the crack reached one side of the cross section of the specimen. When the crack developed into a certain depth of the specimen then final instantaneous fracture occurred. Compared with the crack initiation life, the crack propagation life was very short. Therefore, the crack initiation life can be regarded as the whole fatigue life of the specimen.



Figure 5. Tensile tests setup-Microscopy System of KEYENCE(M).



Figure 6. The fracture surface of designed T- type specimen (a), the crack growth path (b).

2.4.1. Constant Amplitude Fatigue Tests

Thirteen different stress amplitudes were chosen as CA loading conditions. Three repeated experiments were conducted for every stress amplitude condition. Table 3 shows

the specific loading conditions. The stress ratio (R) of all loading conditions is 0.1. According to the recommendation of BS7608 [43], all the fatigue tests were stopped when the cyclic number was larger than 10^7 if fatigue failure didn't appear.

Table 3. Loading conditions of constant amplitude (CA) loading tests.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13
σ_a	105	100	95 0 1	90 0.1	85	80	75	70	55	53	50	45	40
K	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

2.4.2. Variable Amplitude Loading Tests

Two-step repeating amplitude fatigue load tests were carried out after CA loading fatigue tests. Figure 7 shows an abridged general view which depicts the loading spectrum of two-step repeating amplitude fatigue load. In the two-step repeating amplitude fatigue load tests, the high cyclic stress and low cyclic stress levels σ_{a1} and σ_{a2} were set to values above and below the CAFL, respectively. The stress ratio of each stress amplitude was R = 0.1. n_1 and n_2 were the number of cycles of each stress levels σ_{a1} and σ_{a2} in a load block. In the experiments, n_1 =20,000, and it is the same for all the experiments in this article. n_2 was different for different loading cycle ratios. For example, when the loading cycle ratio is 1:1, n_2 =20,000. When the loading cycle ratio is 1:2, n_2 =40,000. Before the failure, n_1 and n_2 kept the same in each loading block for a certain loading cycle ratio. When the failure occurred in the experiments, the failure might appear when the high or the low stress was applied since it is cyclic loading. n_1 was the instantaneous number at the failure moment and recorded in the experiment, not 20,000 any longer, if the failure appeared with the high stress applied. Correspondingly, n_2 was the instantaneous number at the moment when the failure was detected with the low stress applied, not the set number any longer.



Figure 7. The loading sequence of two-step repeating test.

3. Results and Discussion

3.1. Constant Amplitude Test Results

The fatigue lives of different CA conditions were obtained with averaging experimental data from three repeated fatigue tests. Table 4 shows the average experimental results of every CA condition. Figure 8 shows the fitting S-N curve of experimental results. From the experiment results, it can be seen that the experimental scatter is small and the linearity agreement is good in the log—log scale.

Specimen No. σ_a [MPa] R		R	Average Cycles to Failure	Three Repeated Fatigue Experiment Results				
C1	105	0.1	273,187	267,358	270,591	281,612		
C2	100	0.1	413,863	395,732	419,934	425,923		
C3	95	0.1	706,895	575,216	719,683	825,786		
C4	90	0.1	896,437	804,140	908,442	976,729		
C5	85	0.1	925,700	1,035,762	898,867	842,471		
C6	80	0.1	975,620	841,147	914,587	1,171,126		
C7	75	0.1	1,156,460	1,400,569	1,075,784	993,027		
C8	70	0.1	1,933,942	1,829,748	1,656,775	2,315,303		
C9	55	0.1	10^{7} +	10^{7} +	10^{7} +	10^{7} +		
C10	53	0.1	10^{7} +	10^{7} +	10^{7} +	$10^{7}+$		
C11	50	0.1	10^{7} +	10^{7} +	10^{7} +	10^{7} +		
C12	45	0.1	10^{7} +	10^{7} +	10^{7} +	10^{7} +		
C13	40	0.1	10^{7} +	$10^{7}+$	$10^{7}+$	$10^{7}+$		

Table 4. CA loading tests of designed T-type specimens.



Figure 8. Results of experimental data and fitting curve.

3.2. Variable Amplitude Fatigue Experiment Results

The loading conditions of designed T-type specimens under variable amplitude test are mainly divided into two types, variable high cyclic stress (stress ratio) and high–low load cycle ratio. Table 5 lists the loading conditions of the test. The load type was a two-step repeating load block, and the low cyclic stress was 50 MPa which was below the CAFL according to the CA fatigue experiment results. Table 6 shows the experimental results of every load condition under a two-step repeating amplitude fatigue load block. The item $\sum n_i$ stands for the cyclic number contributed by the corresponding cyclic stress amplitude σ_{ai} and the item $\sum (n_1 + n_2)$ stands for the total fatigue life of designed T-type specimen when fatigue failure occurs. The item N_{f1} and N_{f2} is the cyclic number of fatigue failure under the cyclic stress of σ_{a1} and σ_{a2} , respectively. N_{f2} is constant and equals 16,000,000 corresponding to $\sigma_{a2} = 50$ MPa, which is calculated by extrapolating the fitting S-N curve in the log-log plot in Figure 8. σ_{a1} is different in different stress ratio cases and N_{f1} can also be calculated by extrapolating the fitting S-N curve in the log-log plot in Figure 8. The calculated values of N_{f1} for different high stresses are also shown in Table 6.

Stugge (MDa)		Specimen No. under Different Load Block (n_1/n_2)					
Stress (MPa) σ_{a1}/σ_{a2}	20,000/20,000 (1:1)	20,000/40,000 (1:2)	20,000/60,000 (1:3)	20,000/80,000 (1:4)			
105/50	R1	R8	R13	R19			
100/50	R2	R9	R14	R20			
95/50	R3	R10	R15	R21			
93/50	-	-	-	R22			
92.5/50	-	-	R16	R23			
91/50	-	-	R17	-			
90/50	R4	R11	R18	-			
87.5/50	R5	R12	-	-			
85/50	R6	-	-	-			
84/50	R7	-	-	-			

Table 5. Test loading conditions of the two-step repea	eating amplitude.
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Table 6. The test results of designed T-type specimens under two-step repeating amplitude loading sequence.

C	First Step	Second Step	$\sum m$		$\sum (m + m)$	
Specimen No.	N _f 1 (Cycle)	N _f 2 (Cycle)	$\sum n_1$	$\sum n_2$	$\sum (n_1 + n_2)$	
R1	293,018	16,000,000	147,790	145,000	292,790	
R2	383,800	16,000,000	200,000	204,431	404,431	
R3	509,075	16,000,000	310,000	315,434	625,434	
R4	689,256	16,000,000	547,533	540,000	1,087,500	
R5	804,793	16,000,000	695,000	702,573	1,397,573	
R6	945,578	16,000,000	1,128,637	1,120,000	2,248,637	
R7	1,007,230	16,000,000	1,544,489	1,530,000	3,174,489	
R8	293,018	16,000,000	173,321	320,000	493,321	
R9	383,800	16,000,000	245,315	480,000	725,315	
R10	509,075	16,000,000	377,466	720,000	1,097,466	
R11	689,256	16,000,000	640,000	1,276,359	1,916,359	
R12	804,793	16,000,000	1,126,710	2,240,000	3,366,710	
R13	293,018	16,000,000	167,548	480,000	657,548	
R14	383,800	16,000,000	260,000	723,971	983,971	
R15	509,075	16,000,000	400,000	1,109,637	1,509,637	
R16	591,961	16,000,000	580,000	1,743,492	2,323,492	
R17	647,055	16,000,000	780,000	2,326,483	3,106,483	
R18	689,256	16,000,000	1,031,126	3,060,000	4,091,126	
R19	293,018	16,000,000	180,000	677,563	837,563	
R20	383,800	16,000,000	260,000	1,042,741	1,302,741	
R21	509,075	16,000,000	460,000	1,811,567	2,271,567	
R22	573,166	16,000,000	680,000	2,705,437	3,385,437	
R23	591,961	16,000,000	906,292	3,600,000	4,506,292	

4. Damage Accumulation of Variable Fatigue Experiment Analysis

The VA experimental results were analyzed in terms of Miner's rule to check its validity and to examine the effect of stress below the CAFL under the two-step repeating load block. The calculation method is as follows:

$$D = \frac{\sum n_1}{N_{f1}} + \frac{\sum n_2}{N_{f2}}$$
(3)

Figure 9 shows the damage accumulation results of designed T-type specimens under the two-step repeating load block by the Miner's rule. Figure 9 shows the damage accumulation value of every condition with a bar graph, and the different colors represent the fatigue damage contributed by each cyclic stress.



Condition No.

Figure 9. Damage accumulation of every condition.

It can be seen that the fatigue damage caused by low cyclic stress below the CAFL is relatively smaller than that caused by high cyclic stress above the fatigue limit. In order to better compare the fatigue damage evolution law of designed T-type specimens under two-step repeating VA loads, the results of the above-mentioned conditions are sorted out, and the variation law of cumulative damage with the high stress under different load cycle ratios is obtained.

As can be seen from Figure 10, the fatigue cumulative damage of designed T-type specimen shows the same change rule under different load cycle ratios. With the increase of high cyclic stress, the cumulative damage value decreases, and the rate slows down gradually. By comparing the cumulative damage of different load cycle ratios under the same high stress, it can be indicated that the greater the cycle ratio, the greater the fatigue cumulative damage of designed T-type specimens. Besides, the rule of fatigue cumulative damage varying with the cycle ratio under different high stresses is obtained. k_1 , k_2 , k_3 and k_4 represent the linear slope of fatigue cumulative damage with the cycle ratio under high-low stress of 105/50, 100/50, 95/50 and 90/50 MPa, respectively.



Figure 10. Fatigue cumulative damage of designed T-type specimens under different cycle ratios.

Under different high-low stress ratios, the fatigue cumulative damage calculated with the change of the cycle ratio based on Miner rule changes linearly, and the slope k of the curve is different. By fitting the relationship between the high stresses in different loading blocks and the slopes k of these curves in Figure 11, as shown in Figure 12, it can be found that the double logarithmic curve satisfies the data linearly. Finally, the logarithmic relationship between the high stress and the slope k of fatigue cumulative damage varying with the cycle ratio is obtained.



Figure 11. Fatigue damage of designed T-type specimens under different high cyclic stresses.



Figure 12. Double logarithmic curve between the high stress and slope *k*.

5. Non-Linear Damage Evaluation

As the load interaction caused the non-linear damage accumulation in the fatigue test with a two-step repeating amplitude loading block, therefore, the linear damage accumulation did not equal one. The parameter D_{nl} which defined the damage value of

load interaction effect, was introduced into the Miner's law to evaluate the influence by the load interaction. The value of D_{nl} was proposed by Kim et al. [32] and could be calculated as the Formula (4).

$$D_{nl} = 1 - D = 1 - \sum_{i=1}^{n} \frac{n_i}{N_i}$$
(4)

When D_{nl} is positive, it indicates that the fatigue performance is damaged by load interaction effect, and when D_{nl} is negative, it indicates that the fatigue performance is strengthened by load interaction effect. The calculating results by the equation (4) were shown in the Figure 13.



Figure 13. The calculation results of the damage value of load interaction effect D_{nl} .

As can be seen from Figure 13, the load interaction effect of high-low cyclic stress above and below CAFL shows different damage or strengthening effects with the change of cyclic ratio and high stress. Under the same cycle ratio, with the increase of high stress, the load interaction effect gradually transforms from strengthening effect to damage effect. Under the same stress, with the decrease of cycle ratio n_1/n_2 , the damage effect decreases gradually at high stress area, and with the decrease of cycle ratio n_1/n_2 at low stress area, the effect of strengthening effect also increases. It can be seen that the load interaction effects of high-low cyclic stress have different damage or strengthening effects on fatigue performance with the change of stress ratio and cycle ratio.

The procedure for fatigue analysis also applies to other ships with variable loading. The linear damage rule must also be updated by considering the nonlinear damage. The form of the nonlinear damage can be developed further according to the actual loading condition.

6. Conclusions

This paper investigated the fatigue characteristics of designed T-type specimen under the two-step repeating load block. The designed T-type joint was common in the ship structure and the fatigue failure always occurred at this type of joint. The two-step repeating load block was introduced to simulate the load environment of voyage line of river-sea going ship and this type of load block was seldom studied systematically.

CA fatigue experiments were conducted first and then VA fatigue experiments. Every CA fatigue experiment was repeated three times. Twenty-three load conditions of VA fatigue experiment were conducted, Miner's rule was used to calculate the damage accumulation, and the load interaction effect of two-step repeating load block was also evaluated through the formula (4). From the analysis by the Sections 4 and 5, the following conclusions could be drawn:

- (1) For the fatigue performance of designed T-type specimens under two-step VA load, the fatigue cumulative damage values calculated by linear Miner rule are not 1. Compared with the cumulative damage caused by high cyclic stress, the cumulative damage caused by low stress below CAFL is relatively small. It is found that the cumulative damage decreases with the increase of the high stress under the same cycle ratio. While under the same high-low load stress ratio, the cumulative fatigue damage increases with the linear increase of the cycle ratio of the low stress to the high stress, and logarithmic curve between the slope *k* and high stress above CAFL is linear.
- (2) Nonlinear cumulative damage D_{nl} is used to evaluate the load interaction between low and high cyclic stress. It is found that the load interaction shows different damage or strengthening effects with the change of low-high load cycle ratio and high cyclic stress. The area of strengthening effect occurs at high cyclic stress and low load cycle ratio.
- (3) From Figure 11, it can be seen that the linear slope of fatigue cumulative damage with the cycle ratio n_2/n_1 increases with the decrease of high stress in the loading block. The slopes k_3 and k_4 represent the linear slope of fatigue cumulative damage with the cycle ratio n_2/n_1 under high-low stress of 95/50 and 90/50 MPa, respectively. The reason is that the high stress in the loading block is closer to the low stress 50 MPa, the fatigue damage caused by both the high and the low stresses is much smaller. When the cycles of low stress take a larger percentage, i.e., a larger ratio of n_2/n_1 , the strengthening effects are more obvious. As shown in Figure 13, two of the three points at the high stress of 95 MPa is in the strengthening effect area. All of the four points at the high stress of 100 MPa or 105 MPa are in the damage effect area.

The method also applies to other ship types, like the ship only voyaging on the sea or ship only voyaging on the inland river. The ranges of the high and low loading levels should be set according to the actual loading on the ship. For the river-sea-going ship in this study, it mostly voyages in the inland river and then the load below the CAFL takes the most part in the loading. That's why the chosen high cyclic loads were larger than the CAFL and the chosen low cyclic loads were below the CAFL. When the ranges of the high and low loading levels in the variable cyclic loading spectra are different, the experiments may show some different results. More investigation will be necessary.

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