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Experimental Study on Fatigue Performance of M24 Twisted-Shear High-Strength Bolt for Assembled Steel Structure

Rong Xing [1,2], Bin Qiu [1] and Honggang Lei [1,*]

[1] College of Civil Engineering, Taiyuan University of Technology, Taiyuan 030024, China
[2] College of Transportation Engineering, Shanxi Vocational University of Engineering Science and Technology, Jinzhong 030032, China
* Correspondence: lhgang168@126.com

Abstract: High-strength bolt connection is a kind of main connection mode of prefabricated steel structures. Due to the insufficient fatigue performance of high-strength bolts, the degree of damage in the steel structure is very serious, so the fatigue performance research of high strength bolts cannot be ignored. The research object of the paper is M24 twisted-shear high-strength bolts in a steel structure buildings. Some special tests and results analysis on the normal fatigue performance were carried out, establishing the fatigue S-N curve of M24 twisted-shear high-strength bolts, revealing the fatigue failure mechanism of M24 torsion-shear high-strength bolts; obtaining the fatigue S-N curve equation; and estimating the fatigue life of high-strength bolts by using the Paris formula. In addition, by comparing the test data in this paper with the constant fatigue test data of high-strength bolts in the existing research literature, it can be seen how the strength grade of the bolts and the pretension force have an impact on the fatigue strength. It is further revealed that the M24 torsion-shear high-strength bolt with full pretension force has twice as long fatigue life than the other two types of bolts. By comparing the test results of M24 and M20 bolts under full pretension, it is known the relation between the fatigue strength of the bolts and diameter decreases. The research data and useful conclusions can provide scientific basis and theoretical reference for the anti-fatigue design of M24 torsion-shear high-strength bolt connection.

Keywords: prefabricated steel structure; M24 twisted-shear high-strength bolt; fatigue failure; pre-tension force; S-N fatigue curve

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1. Introduction

High-strength bolt connection is the main connection mode of prefabricated steel structures, and it is widely applied in practical engineering because of its advantages of convenient installation, easily ensuring the construction quality, and high construction efficiency. On-site bolt connection is fast and convenient, but fatigue damage of the bolt nodes will occur under the action of long-term repeated load, so the fatigue performance of bolt nodes cannot be ignored. Since the German engineer W. A. J. Albert proposed the fatigue problem as early as 1829, many scholars have paid attention to it and studied it [1], and different studies on structures' fatigue problems are gradually appearing, especially considering different kinds of factors such as structural details, structure materials, etc. [2–9].

So, the fatigue problem of high-strength bolt connection is also being paid more and more paid attention. Saranik et al. conducted fatigue test research on high-strength bolts, putting forward the effect of stress concentration on the fatigue performance [10]; Lei et al. have carried out a lot of test and theory research on high-strength bolts' fatigue problems, and the stress concentration coefficient of M14, M20, M24, M30, M33, M39, M36, M52, M60 was established; the S-N curve was obtained by unified regression analysis; the corresponding constant fatigue design method was established; and the variable fatigue life was estimated with the help of Corten–Dolan theory [11]. Hao et al. fitted the fatigue crack extension rate of S355 and S690 steel by the Walker formula, and the average stress effect was included, based on which random analysis was conducted by the Monte Carlo method, and it was concluded that the guaranteed rate of fatigue crack expansion parameters of steel is 95%, 97.7%, and 99%, respectively [12]. Jiao et al. carried out static analysis of high-strength bolt joints and metallographic analysis of fatigue fracture through a constant amplitude fatigue test, and in 2021 completed the constant amplitude fatigue test of 21 M24 high-strength large hexagon head bolts made of 35K steel and of grade 8.8 with an MTS fatigue tester [13]. Huang carried out the constant amplitude fatigue test of 14 M24 high-strength large hexagon head bolts with the help of an MTS fatigue testing machine [14]. Guo et al. analyzed the fatigue performance of the Q690D high-strength steel bolt connection through the fatigue test, and fitted the S-N curve according to the test data, deducing the fatigue injury formula through the test data [15]. Bai et al. developed a general lumped damage simulation model for predicting the fatigue damage life-cycle and the associated crack propagation in the full range of elastic and plastic amplitudes [16]. Niu et al. analyzed the relationship among defects, fatigue strength, and fatigue curves to extrapolate the probabilistic fatigue curves for AM materials [17]. Li et al. proposed a new probabilistic fatigue model for life assessment by combining the weakest link theory with the strain energy concept, and utilized experimental data of GH4169, TC4, and TC11 alloys with different geometries to carry out model validation and comparison [18].

However, most fatigue studies are focused on high-strength bolts with a grid structure. Currently, there is little research about sudden fatigue failure of a fabricated steel structure buildings Therefore, on the basis of previous research on the fatigue failure type and mechanism of the steel structure, we carried out constant amplitude fatigue tests on the M24 twisted-shear high-strength bolts used in the fabricated steel structure residence. In the study, the nodes between the beam and the column of the fabricated steel structure fully apply twisted-shear high-strength bolts. It is the study prerequisite that the full pretension force was applied to the twisted-shear high-strength bolts before the experiment. Through analyzing test data, we have established the fatigue S-N curve equation of M24 twisted-shear high-strength bolt connection, revealed the fatigue failure mechanism, and developed the design method for constant amplitude fatigue based on the nominal stress, estimating the fatigue life of M24 twisted-shear high-strength bolts based on broken mechanics. In total, this study will provide the scientific basis and theoretical reference for the anti-fatigue design on M24 twisted-shear high-strength bolt connection.

2. Experimental Methods

2.1. Specimen Design

2.1.1. M24 Torsional Shear High-Strength Bolt Connection

Figure 1 shows the M24 torsion-shear high-strength bolt used in the fatigue test, the nominal diameter of which is 24 mm; the length of which is 100 mm; and the composition of which is ML20MnTiB steel, produced in China. It is constituted of one bolt, one nut, and one gasket, exactly the same as the high-strength bolts used in an actual fabricated steel structure. Before the fatigue tests, the bolts' appearance was visually checked, ensuring that there were no initial defects such as cracks, rust, or bumps on the bolts. The basic performance indexes of the high-strength bolt connection are shown in Table 1.

Table 1. High-strength bolt type, performance grade, and related specifications.

Type		Material or Performance Grade	Standard
torsion-shear high-strength bolt connection	bolt	10.9S	*Torsion-shear High-strength Bolt Link for Steel Structure (GB/T 3632-2008)* [19]
	nut	10H	
	gasket	35 steel/45 steel	

Figure 1. The high-strength bolt connection.

2.1.2. T-Type Connector

By reference to the *Design Standard for Steel Structure (GB50017-2017)* [20], a set of T-type load devices was designed for the axial tensile fatigue test of torsion-shear high-strength bolts according to the loading requirements of the fatigue test, considering the connection form and force characteristics of high-strength bolts. The specific processing size of the T-type connector is shown in Figure 2. The loading device is made of Q345B steel. The thickness of the plate is 25 mm; the thickness of the reinforced rib is 14 mm. The connection between the plates includes an open groove weld with equal strength. The steel of the device meets the quality requirements of Q345 of *Low Alloy High-Strength Structural Steel (GB/T1591-2018)* [21], and the strength and stiffness of the loading device meet the requirements of the fatigue test.

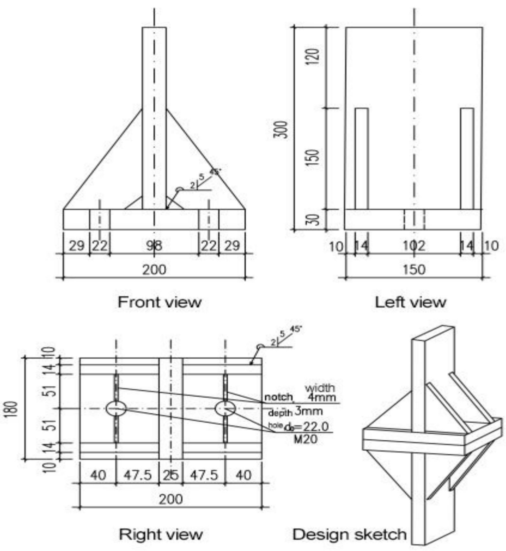


Figure 2. T-type connectors.

2.2. Mechanical Properties of Bolt's Material

In order to obtain the static mechanics properties of the M24 twisted-shear high-strength bolt and provide a reference basis for the fatigue test loading scheme, the static tensile test of the M24 twisted-shear high-strength bolt was carried out before the fatigue test. Meanwhile, according to *Metallic materials—Tensile testing—Part 1: Method of Test at Room Temperature (GB/T228.1-2010)* [22], three M24 twisted-shear high-strength bolt specimens randomly selected were set as a group, No. of which was a, b, and c respectively, and they were processed into standard specimens by machine tools, as shown in Figure 3. The static tensile test of the standard bolt sample was conducted by the MTS test machine, as shown in Figure 4. The material properties obtained from the static tensile test are listed in Table 2. It is seen from the results in the table that the average ultimate tensile strength of the M24 torsion-shear high-strength bolt is 1106.5 MPa, and its average conditional yield strength is 1029.0 MPa. Therefore, the mechanical properties meet the relevant regulations and requirements of the current national standard—*Torsional shear High Strength Bolt Link for Steel Structure (GB/T3632-2008)* [19]. Then, these properties were applied to the determination of the suitable loading stress level.

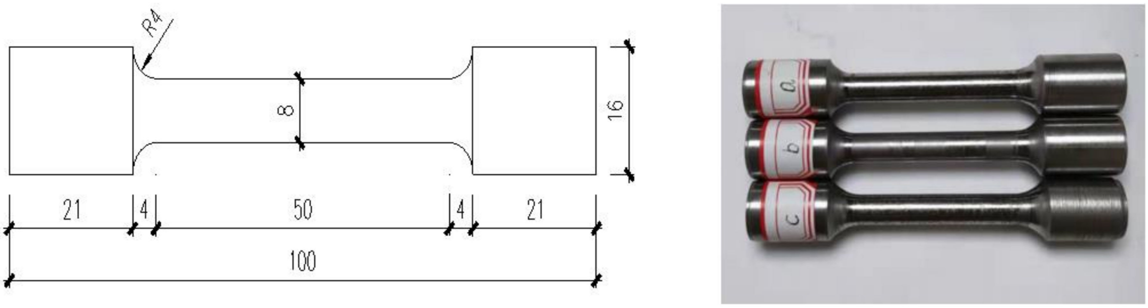


Figure 3. Standard tensile specimen for M24 torsional shear-type high-strength bolt.

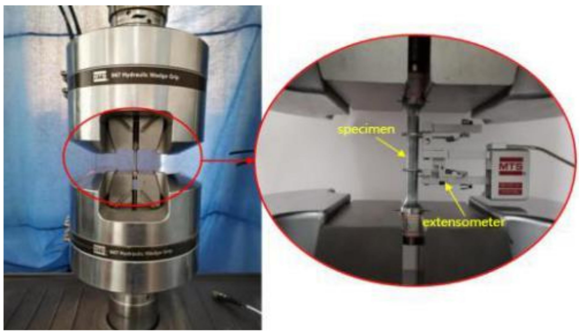


Figure 4. Schematic diagram of test loading.

Table 2. Test results for high-strength bolts.

No.	Strength (MPa)				Modulus of Elasticity (GPa)		Extensibility $\bar{\delta}$
	$\sigma_{0.2}$	$\overline{\sigma_{0.2}}$	σ_b	$\overline{\sigma_b}$	E	$\bar{E}$	
a	1008.4		1084.4		208.9		
b	1040	1029	1117.8	1106.5	209.1	207.9	13.4
c	1038.6		1117.2		205.6		

2.3. Testing Program and Procedure

2.3.1. Fatigue Test Equipment

The constant amplitude fatigue test of the M24 twisted-shear high-strength bolt connection was carried out in the civil engineering laboratory of Taiyuan University of Technology with a room temperature atmospheric environment. The test equipment included an MTS Landmark 370.50 hydraulic servo fatigue test machine. The device has high load accuracy and the dynamic load capability of 500 kN; the load frequency can reach 100 Hz at most; the loading displacement measurement accuracy reaches 0.00028 mm.

2.3.2. Process and Method of the Test

Following the relevant regulations of *Metallic materials-Tensile testing-Axial-Force - Controlled Method (GB/T3075-2008)* [23], 10 loading stress levels corresponding to different stress ranges were obtained for the fatigue test according to the above mechanical properties of M24 twisted-shear high-strength bolts, as shown in Table 3.

The stress was calculated as the following Formula (1):

$$\sigma = P/A_{eff} \tag{1}$$

where P is the axial tension load; A_{eff} is the effective area of the bolt.

The stress ratio in cyclic loading was set as the following Formula (2):

$$R = \frac{\sigma_{min}}{\sigma_{max}} = 0.6 \tag{2}$$

where σ_{max} and σ_{min} are the maximum and minimum stress.

And the stress range was calculated as the following Formula (3):

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \tag{3}$$

Considering the factors of this test equipment and loading device, etc., the specimens were tested under a constant amplitude sinusoidal loading at a 2~7 Hz frequency; the maximum stress level is about $0.6 f_y$; and the stress ratio R is 0.6.

Table 3. Details of testing program.

Level	σ_{max} (MP)	$\Delta\sigma$ (MP)	Number	Level	σ_{max} (MP)	$\Delta\sigma$ (MP)	Number
L1	400	160	2	L6	515	206	2
L2	475	190	2	L7	525	210	2
L3	485	194	1	L8	550	220	9
L4	500	200	2	L9	575	230	2
L5	512.5	205	1	L10	600	240	2

The key to the test is that the high-strength bolts should be put the pretension force in order to achieve the purpose of reliable connection. The method of applying the pretension force is shown in Figure 5. When the tail of the torsional shear high-strength bolt is shaken off, the pretension force value of the bolt reaches the specified requirements and, meanwhile, the pretension force of the bolt reaches the specified value 225 kN. The fatigue test loading of the M24 torsion high-strength bolt connection is shown in Figure 6.

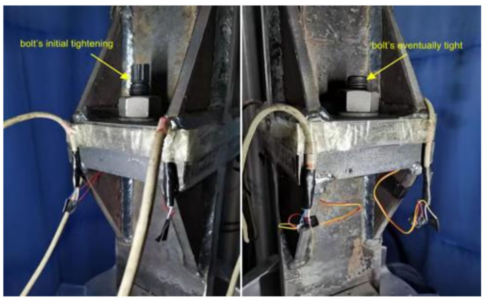


Figure 5. Comparison of M24 torsional shear-type bolt before and after pretightening application.

There are three steps in the constant amplitude fatigue test. The specific test process is that, first, two high-strength bolts are connected to the left and right sides of the T sample, adjusting the position of two T parts to keep them in the center, and they are finally tightened to maintain the coaxial degree between the T combination sample and fixture. The upper and lower ends of the T combination sample are clamped respectively by the MTS fatigue test machine, in order to put axial tensile force on the bolts; secondly, the samples are loaded after installing, specifically recording the test process and related conditions. During the test, if bolts break or other damage occurs, the MTS test machine will stop loading. When the test stops, the cycle time is recorded as the fatigue life of the damaged bolt, and the fatigue failure map is made; thirdly, the broken bolts are replaced, the load stress amplitude is reset, and the first two steps are repeated to carry out a normal amplitude fatigue test of the next high-strength bolt until the test ends.

Figure 6. A general view of fatigue test loading for M24 high-strength bolts.

3. Experimental Results

3.1. Fatigue Failure Mode

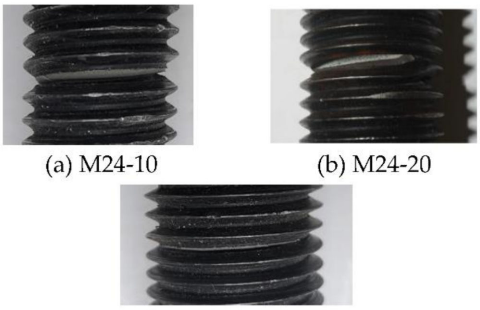
The total 25 M24 twisted-shear high-strength bolts were subjected to the fatigue test. Their fatigue failure forms are presented in Figure 7. It is seen that all the fatigue failures in the test occurred at the root of the high-strength bolt thread, and the failure of most of bolts were located in the first circle of the thread where the nut was engaged with the bolt. Through further analysis, the fatigue failure form of the above bolts can be summarized into the following three modes, as is shown in Table 4.

Figure 7. Fatigue failure of specimens.

Table 4. Fatigue failure mode for high-strength bolts.

Model No.	Fatigue Fracture Characteristic	Illustration
1	Fatigue fracture occurred at the first circle of the bite between the bolt rod and the nut, and the number of bolts where fatigue damage occurred accounts for about 85% of the total number of specimens. It is the main form of damage in this fatigue test. The reason is that the fixing effect of the nut leads to the thread gap root of the first circle between the nut and the thread has a serious stress concentration, the fatigue notch effect is significant, and the initial fatigue crack easily occurs.	

Table 4. *Cont.*

Model No.	Fatigue Fracture Characteristic	Illustration
2	There is only one bolt fatigue failure which is of this type, which is far away from the thread bottom where the nut meshes, and it destroyed the first circle of the thread of the transition area between the bolt rod (smooth part) and the thread.	
3	The bolts were not completely broken, but some obvious cracks appeared in the thread, which seriously affected the bearing capacity of the bolts. There were three bolts with this damage mode. If the loading continued, the bolt also broke at the thread.	 (a) M24-10 (b) M24-20 (c) M24-23

3.2. Fatigue S-N Curve

In total, 25 satisfactory constant amplitude fatigue tests of the M24 twisted-shear high-strength bolts were carried out. The results of fatigue tests are shown in Tables 5–8. It is seen that M24-1 and M24-2's had more than 5 million stress cycles, while M24-13, M24-14, and M24-15 with prestress relaxation during secondary loading had a significantly shorter fatigue life.

Table 5. Constant amplitude fatigue test results of M24 torsional shear-type high-strength bolt with pretension (σ_{max} = 400–500 MP).

No.	Loading Stress/MPa				Stress Amplitude/MPa	Fatigue Life/Time
	σ_{max}	σ_{min}	σ_m	R	$\Delta\sigma$	N
M24-1	400	240	320	0.6	160	5,100,006
M24-2	400	240	320	0.6	160	5,100,006
M24-3	475	285	380	0.6	190	2,273,480
M24-4	475	285	380	0.6	190	2,352,282
M24-5	485	291	388	0.6	194	751,375
M24-6	500	300	400	0.6	200	1,221,394
M24-7	500	300	400	0.6	200	1,298,395

Table 6. Constant amplitude fatigue test results of M24 torsional shear-type high-strength bolt with pretension (σ_{max} = 512.5–525 MP).

No.	Loading Stress/MPa				Stress Amplitude/MPa	Fatigue Life/Time
	σ_{max}	σ_{min}	σ_m	R	$\Delta\sigma$	N
M24-8	512.5	307.5	410	0.6	205	1,546,630
M24-9	515	309	412	0.6	206	492,189
M24-10	515	309	412	0.6	206	492,189
M24-11	525	315	420	0.6	210	535,942
M24-12	525	315	420	0.6	210	567,354

Table 7. Constant amplitude fatigue test results of M24 torsional shear-type high-strength bolt with pretension (σ_{max} = 550 MP).

No.	Loading Stress/MPa				Stress Amplitude/MPa	Fatigue Life/Time
	σ_{max}	σ_{min}	σ_m	R	$\Delta\sigma$	N
M24-13	550	330	440	0.6	220	153,563
M24-14	550	330	440	0.6	220	205,678
M24-15	550	330	440	0.6	220	196,329
M24-16	550	330	440	0.6	220	370,241
M24-17	550	330	440	0.6	220	457,271
M24-18	550	330	440	0.6	220	457,271
M24-19	550	330	440	0.6	220	642,275
M24-20	550	330	440	0.6	220	642,275
M24-21	550	330	440	0.6	220	441,443

Table 8. Constant amplitude fatigue test results of M24 torsional shear-type high-strength bolt with pretension (σ_{max} = 575–600 MP).

No.	Loading Stress/MPa				Stress Amplitude/MPa	Fatigue Life/Time
	σ_{max}	σ_{min}	σ_m	R	$\Delta\sigma$	N
M24-22	575	345	460	0.6	230	282,422
M24-23	575	345	460	0.6	230	282,422
M24-24	600	360	480	0.6	240	195,186
M24-25	600	360	480	0.6	240	214,782

Generally, the relationship between the external load and its corresponding fatigue life is described by the S-N curve. The empirical equation of the S-N curve in the form of a power function is given by

$$N\cdot(\Delta\sigma)^m = C \tag{4}$$

The S-N curve in logarithmic form can be expressed as follows:

$$\lg N = -m\lg(\Delta\sigma) + \lg C \tag{5}$$

Under the 97.72% reliability probability, the formula obtained is as follows:

$$\lg N = -m\lg(\Delta\sigma) + \lg C - 2s \tag{6}$$

Combined with the data in the fatigue test process analysis in Tables 4–7, M24-13~15 were considered as abnormal data points and eliminated due to the prestress relaxation of the secondary loading. Furthermore, over 5 million stress cycle data points of the bolts M24-1 and M24-2 also did not participate in fitting the S-N curve. Therefore, the valid data of the other 20 bolts were used to fit the power multiplier S-N curves. Taking the stress amplitude as the parameter, the constant amplitude power regression curve and fatigue S-N curve are presented in Figures 8 and 9, respectively, where the logarithmic equation for the corresponding part of the oblique line of the S-N curve in Figure 9 can be developed as Equation (7).

$$\lg N = 32.365 - 11.419\lg(\Delta\sigma) \tag{7}$$

It can be seen from Figures 8 and 9 that the fatigue life of the specimens is relatively scattered at the same stress amplitude, but in total the fitting correlation coefficient of the bolt test data is highly satisfied, the value of which is about 0.8. Moreover, the test data follow the trend that the lower the stress range, the longer the fatigue life. Additionally, by calculating the standard deviation of fatigue test data, we can acquire the S-N curve equation under 97.72% survival probability, as shown in Equation (8).

$$\lg N = 32.365 - 11.419\ \lg\Delta\sigma - 2 \times 0.141 \tag{8}$$

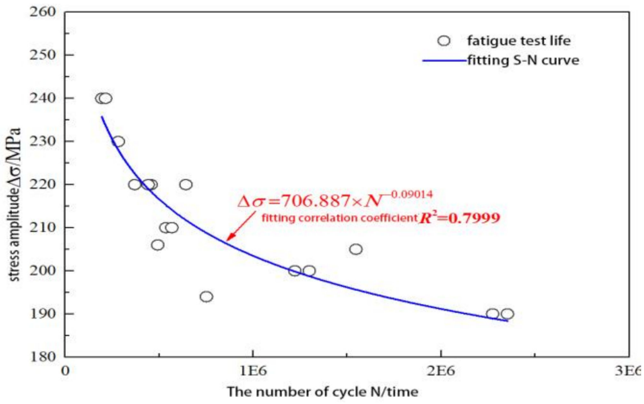


Figure 8. The power regression S-N curve with the stress range as parameter.

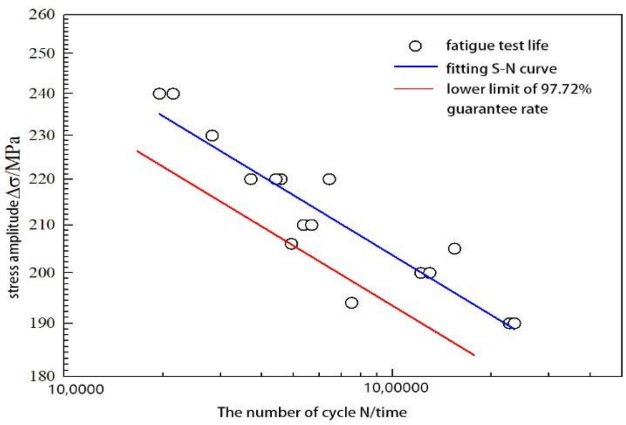


Figure 9. S-N curve of M24 high-strength bolts obtained from the tests.

4. The Design Method for Constant Amplitude Fatigue Based on the Nominal Stress

4.1. The Establishment of the Formula

The nominal stress method takes the nominal stress of the parts as the parameter. Through a lot of fatigue tests, the fatigue S-N curves of different structural details are established, so as to design the fatigue strength or fatigue life of the structure. The high cycle fatigue problem mainly involves this method. At present, the nominal stress amplitude method is still the representative fatigue design and checking method in the steel structure design specifications of various countries. Therefore, we used the nominal stress amplitude as the control parameter, establishing the allowable stress amplitude fatigue design method of M24 twisted-shear high-strength bolts under the condition of full pretension. The method can be applied in practical engineering and check the fatigue strength of M24 twisted-shear high-strength bolts.

The calculating formula with the nominal stress amplitude as the design parameter is as follows:

$$\Delta\sigma \le [\Delta\sigma] \tag{9}$$

$$[\Delta\sigma] = \left(\frac{C}{N}\right)^{1/\beta} \tag{10}$$

4.2. Application of The Formula

According to the fatigue S-N curve fitting formula, the value of the fatigue design parameter β is 11.419, and the value of the fatigue design parameter C is 12.106×10^{31}. It can be seen that when the fatigue life of the bolt is 5×10^6, the value of normal amplitude fatigue limit $[\Delta\sigma]_{5\times10^6}$ is 167.0 MP, and when the fatigue life of the bolt is 2×10^6, the value of the allowable stress amplitude $[\Delta\sigma]_{2\times10^6}$ is 187.0 MP.

5. Estimating the Fatigue Life of M24 High-Strength Bolts Based on Broken Mechanics

5.1. Parameter Determination

The values of the parameters are shown in Table 9.

Table 9. The value of parameters.

Parameter	a_0	a_c (mm)	α	C	m
	0.01 mm, 0.02 mm, 0.05 mm	21.19	1.1215	7.04×10^{-12}	3

5.2. Estimation of Fatigue Life of M24 Twisted-Shear High-Strength Bolt

According to the fatigue crack extension parameters determined above, the fatigue life of M24 high-strength bolts is estimated based on the Paris formula, and the results are listed in Tables 10–12.

According to the comparison of the predicted life and the test life in the tables above, it is basically feasible to estimate the fatigue life of high-strength bolts by using the Paris formula, which can generally reflect the changing trend of fatigue life.

Table 10. Estimated fatigue life of M24 high-strength bolt (a_0 = 0.01 mm).

No.	σ_{max}/MPa	σ_{min}/MPa	$\Delta\sigma_n$/MPa	Predicted Life/Time	Test Life/Time
M24-1	400	240	160	2,731,721	5,100,006
M24-2	400	240	160	2,731,721	5,100,006
M24-3	475	285	190	1,631,306	2,273,480
M24-4	475	285	190	1,631,306	2,352,282
M24-5	485	291	194	1,532,467	751,375
M24-6	500	300	200	1,398,641	1,221,394
M24-7	500	300	200	1,398,641	1,298,395
M24-8	512.5	307.5	205	1,298,777	1,546,630
M24-9	515	309	206	1,279,955	492,189
M24-10	515	309	206	1,279,955	492,189
M24-11	525	315	210	1,208,199	535,942
M24-12	525	315	210	1,208,199	567,354
M24-13	550	330	220	1,050,820	153,563
M24-14	550	330	220	1,050,820	205,678
M24-15	550	330	220	1,050,820	196,329
M24-16	550	330	220	1,050,820	370,241
M24-17	550	330	220	1,050,820	457,271
M24-18	550	330	220	1,050,820	457,271
M24-19	550	330	220	1,050,820	642,275
M24-20	550	330	220	1,050,820	642,275
M24-21	550	330	220	1,050,820	441,443
M24-22	575	345	230	919,629	282,422
M24-23	575	345	230	919,629	282,422
M24-24	600	360	240	809,399	195,186
M24-25	600	360	240	809,399	214,782

Table 11. Estimated fatigue life of M24 high-strength bolt (a_0 = 0.02 mm).

No.	σ_{max}/MPa	σ_{min}/MPa	$\Delta\sigma_n$/MPa	Predicted Life/Time	Test Life/Time
M24-1	400	240	160	1,913,851	5,100,006
M24-2	400	240	160	1,913,851	5,100,006
M24-3	475	285	190	1,142,897	2,273,480
M24-4	475	285	190	1,142,897	2,352,282
M24-5	485	291	194	1,073,650	751,375
M24-6	500	300	200	979,892	1,221,394
M24-7	500	300	200	979,892	1,298,395
M24-8	512.5	307.5	205	909,927	1,546,630
M24-9	515	309	206	896,740	492,189
M24-10	515	309	206	896,740	492,189
M24-11	525	315	210	846,467	535,942
M24-12	525	315	210	846,467	567,354
M24-13	550	330	220	736,207	153,563
M24-14	550	330	220	736,207	205,678
M24-15	550	330	220	736,207	196,329
M24-16	550	330	220	736,207	370,241
M24-17	550	330	220	736,207	457,271
M24-18	550	330	220	736,207	457,271
M24-19	550	330	220	736,207	642,275
M24-20	550	330	220	736,207	642,275
M24-21	550	330	220	736,207	441,443
M24-22	575	345	230	644,295	282,422
M24-23	575	345	230	644,295	282,422
M24-24	600	360	240	567,067	195,186
M24-25	600	360	240	567,067	214,782

Table 12. Estimated fatigue life of M24 high-strength bolt a_0 = 0.05 mm.

No.	σ_{max}/MPa	σ_{min}/MPa	$\Delta\sigma_n$/MPa	Predicted Life/Time	Test Life/Time
M24-1	400	240	160	1,188,130	5,100,006
M24-2	400	240	160	1,188,130	5,100,006
M24-3	475	285	190	709,517	2,273,480
M24-4	475	285	190	709,517	2,352,282
M24-5	485	291	194	666,528	751,375
M24-6	500	300	200	608,323	1,221,394
M24-7	500	300	200	608,323	1,298,395
M24-8	512.5	307.5	205	564,888	1,546,630
M24-9	515	309	206	556,701	492,189
M24-10	515	309	206	556,701	492,189
M24-11	525	315	210	525,492	535,942
M24-12	525	315	210	525,492	567,354
M24-13	550	330	220	457,042	153,563
M24-14	550	330	220	457,042	205,678
M24-15	550	330	220	457,042	196,329
M24-16	550	330	220	457,042	370,241
M24-17	550	330	220	457,042	457,271
M24-18	550	330	220	457,042	457,271
M24-19	550	330	220	457,042	642,275
M24-20	550	330	220	457,042	642,275
M24-21	550	330	220	457,042	441,443
M24-22	575	345	230	399,982	282,422
M24-23	575	345	230	399,982	282,422
M24-24	600	360	240	352,039	195,186
M24-25	600	360	240	352,039	214,782

6. Results and Discussion

6.1. Influence of the Bolts' Pretension on the Fatigue Strength

In existing fatigue performance research of M24 high-strength bolts [13], with the help of an MTS fatigue test machine, a normal amplitude fatigue test on 21 M24 high-strength large hexagon head bolts that were of 8.8 grade and made of 35 K steel was carried out. The torque value of the pretension force put on the bolt in the test was from 230 to 360 N·m. Test loading stress ratio R was equal to 0.5, σ_{max} was from 180 to 460, increasing by 10 MP every time to 300 MP and adding 20 MP per level from 300 MP. σ_{min} was from 90 to 150, increasing by 5 MP to 150 MP, and adding 20 MP per level from 150 MP. The constant stress amplitude fatigue of M24 high-strength large hexagon head bolts for fabricated steel structures was compared. The results of the constant amplitude fatigue test are shown in Table 13.

Table 13. Constant amplitude fatigue test data of M24 high-strength bolts with large hexagon head.

No.	Stress/MPa				Stress Amplitude/MPa	Fatigue Life/Time
	σ_{max}	σ_{min}	R	The Torque Value of the Pretension Force/(N·m)	$\Delta\sigma$	N
1	180	90	0.5	300	90	2,426,465
2	190	95	0.5	360	95	2,477,335
3	200	100	0.5	300	100	2,791,911
4	210	105	0.5	230	105	1,748,722
5	220	110	0.5	300	110	1,422,068
6	230	115	0.5	230	115	1,152,669
7	240	120	0.5	330	120	818,742
8	250	125	0.5	250	125	532,491
9	260	130	0.5	330	130	684,474
10	270	135	0.5	270	135	778,867
11	280	140	0.5	330	140	296,540
12	290	145	0.5	190	145	539,048
13	300	150	0.5	360	150	523,784
14	320	160	0.5	360	160	385,283
15	340	170	0.5	360	170	189,234
16	360	180	0.5	240	180	190,009
17	380	190	0.5	240	190	130,256
18	400	200	0.5	240	200	168,523
19	420	210	0.5	270	210	84,119
20	440	220	0.5	270	220	81,535
21	460	230	0.5	270	230	68,781

In existing fatigue performance research of M24 high-strength bolts [14], the constant amplitude fatigue test of 14 M24 high-strength hexagon head bolts with the help of an MTS fatigue test machine was completed, in which the material (ML20MnTiB) and strength grade (10.9) of the bolts were exactly the same as those of the test in this paper. The torque value of the pretension force put on the bolt in the test was from 200 to 300 N·m, and the test loading stress ratio R was equal to 0.64. The results of normal amplitude fatigue tests in the literature are listed in Table 14.

In order to compare the constant amplitude fatigue performance of M24 high-strength bolts under different conditions, the relationship between the stress range and fatigue life was investigated. Taking the nominal stress amplitude as the parameter, the power regression curve and S-N curve were established in the same coordinate system, as shown in Figures 10 and 11.

Table 14. Constant amplitude fatigue test data of M24 high-strength bolts with large hexagon head.

No.	Stress/MPa				Stress Amplitude/MPa	Fatigue Life/Time
	σ_{max}	σ_{min}	σ_m	R	$\Delta\sigma$	N
1	1000	640	820	0.64	360	21,500
2	1133	725	929	0.64	408	12,800
3	430	278	354	0.64	155	411,700
4	450	288	369	0.64	162	319,000
5	470	300.8	385.4	0.64	169.2	306,900
6	490	313.6	401.8	0.64	176.4	299,200
7	800	512	656	0.64	288	46,000
8	650	416	533	0.64	234	113,000
9	600	384	492	0.64	216	159,300
10	550	352	451	0.64	198	179,200
11	400	256	328	0.64	144	668,200
12	350	224	287	0.64	126	1,305,600
13	370	236.8	303.4	0.64	133.2	732,700
14	360	230.4	295.2	0.64	129.6	915,600

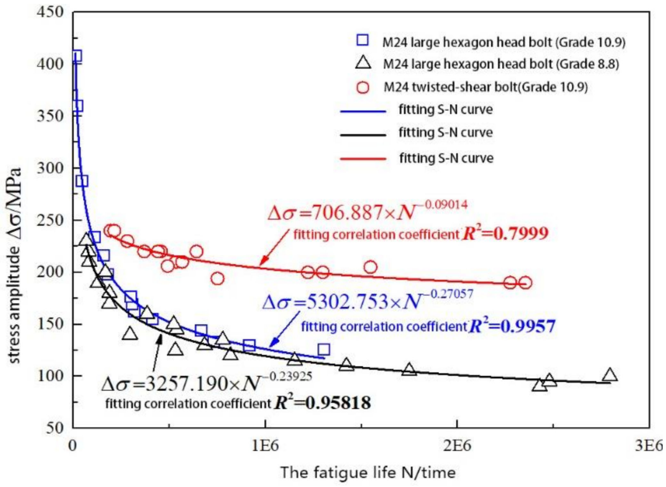


Figure 10. Comparing fatigue test results of three bolts.

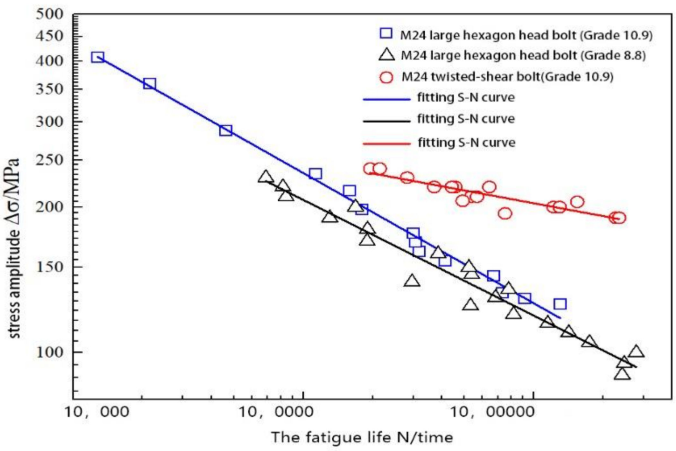


Figure 11. Comparing fatigue test results of three bolts (double logarithmic S-N curve).

Combined with the data in the fatigue test process analysis in Tables 5–8 and Tables 12–14, taking the stress amplitude as the parameter, the constant amplitude power regression curve and fatigue S-N curve are presented in Figures 10 and 11, respectively, where the logarithmic equation for the corresponding part of the oblique line of the S-N curve in Figure 11 can be developed as the first and the second equation in Table 16.

As can be seen above, the following conclusions can be drawn:

1. The grade 10.9 M24 twisted-shear high-strength bolt has a longer fatigue life, while the grade 8.8 M24 large hexagonal bolt has the shortest fatigue life;
2. Through comparing the test results of the M24 twisted-shear high-strength bolt with 100% pretension and of grade 10.9 and the grade 8.8 M24 large hexagonal bolt that only experienced 20~40% of the pretension torque value, it is seen that the pretension force of the bolt will have a great impact on the fatigue strength. The higher the value of the pretension force, the higher the fatigue strength of the bolt.

6.2. Influence of Bolt Diameter on Fatigue Strength

In existing fatigue performance research of M20 twisted-shear high-strength bolts [24,25], the material (ML20MnTiB) and strength grade (10.9) used in this test are exactly the same as the bolts tested, and the test loading stress ratio R is equal to 0.1. The value range of the largest stress is 350–550 MPa. The value range of the smallest stress is 35–55 MPa, with both showing a gradual decreasing trend. However, the fatigue life becomes longer and longer. The maximum value is 1,021,264 N/time; the minimum is 28,103 N/time. The results of normal amplitude fatigue tests in the literature are listed in Table 15.

Table 15. Constant amplitude fatigue life of M20 bolts under full pretension force.

No.	Fatigue Life/Time N	No.	Fatigue Life/Time N
M20-1	28,103	M20-7	106,049
M20-2	32,223	M20-8	124,244
M20-3	34,656	M20-9	293,280
M20-4	49,162	M20-10	1,021,264
M20-5	79,504	M20-11	602,672
M20-6	87,079	M20-12	1,580,019

In order to compare the constant fatigue performance of M24 and M20 twisted-shear high-strength bolts under full pretension, the double-log S-N curve is made in the same coordinate system according to the fatigue test data in Tables 5–8 and in Table 15, as is shown in Figure 12, and the logarithmic equation for the corresponding part of the oblique line of the S-N curve is developed as the third equation in Table 16.

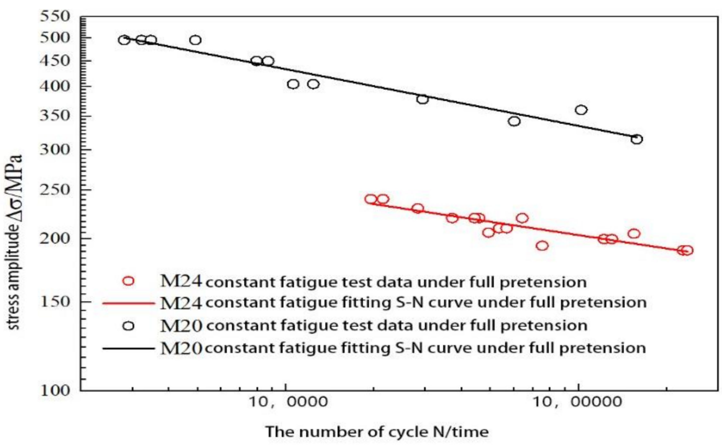


Figure 12. Comparison of fatigue test data of M24 and M20 bolts.

Table 16. Constant amplitude fatigue S-N curve equation of M24 and M20 high-strength bolts with large hexagon head.

The Type of Bolt	Equation	The Stress Amplitude/MP (2 Million Fatigue Life; the Reliability Level of 97.72%)
10.9-grade M24 twisted-shear bolt	$\lg N = 32.365 - 11.419 \lg \Delta\sigma - 2 \times 0.141$	167
8.8-grade M24	$\lg N = 14.697 - 4.188 \lg \Delta\sigma - 2 \times 0.106$	90
10.9-grade M24	$\lg N = 13.821 - 3.720 \lg \Delta\sigma - 2 \times 0.056$	98
M20 twisted-shear bolt	$\lg N = 27.023 - 8.348 \lg \Delta\sigma - 2 \times 0.1535$	278

The constant amplitude fatigue S-N curve equations of the 8.8-grade M24 high-strength large hexagonal head bolt, the 10.9-grade M24 high-strength large hexagonal head bolt, and M20 torsion-shear bolt were obtained by regression fitting, as shown below.

As can be seen above, the following conclusions can be drawn:

1. Under full pretension, the fatigue test data of the M20 twisted-shear high-strength bolt have higher values than those of the M24 bolt.
2. Under the guaranteed probability of 97.72%, the stress amplitude of the M20 twisted-shear high-strength bolt corresponding to 2 million fatigue life is about 278.0 MPa, which is greater than the stress amplitude, the value of which is 181.0 MPa for the M24 bolt. It was indicated that under the same stress amplitude the M20 twisted-shear high-strength bolt has a longer fatigue life than the M24 twisted-shear high-strength bolt.
3. The fatigue strength will decrease when the bolt diameter increases. The reason is that, due to the influence trend that the bolt diameter has on the fatigue strength, when the diameter of the bolt increases, the concentration of the stress between the thread and the bolt will be exacerbated; meanwhile, some defects or impurities will occur during the process of heat treatment.

7. Conclusions

This research included a total of 25 constant amplitude fatigue experiments to study the fatigue performance of M24 twisted-shear high-strength bolts. The design method for constant amplitude fatigue based on the nominal stress was established. In order to evaluate the fatigue performance of M24 twisted-shear high-strength bolts exactly, comparisons between fatigue test data obtained from M24 high-strength bolts of grades 8.8 and 10.9 with a large hexagon head under 20–40% pretension force and M20 bolts under full pretension force were completed. The following conclusions could be drawn based on the findings from the above experiments.

1. Fatigue failure of all M24 twisted-shear high-strength bolts in the test occurred at the root of the high-strength bolt thread, and among them most bolts were damaged at the first circle of the thread between the nut and the bolt, where there was a serious stress concentration, and the fatigue gap effect was significant.
2. The constant amplitude fatigue S-N curve was obtained by test data fitting and the corresponding S-N curve equation of M24 twisted-shear high-strength bolts with the stress range as the design parameter, and the fitting correlation coefficient of the test data was about 0.8. Under the guaranteed rate of 97.72%, the allowable stress amplitude of 5 million fatigue life is about 167.0 MPa; that of 2 million fatigue life is about 181.0 MPa.
3. According to the fatigue S-N curve fitting formula, the value of the fatigue design parameter is 11.419, and the value of the fatigue design parameter C is 12.106×10^{31}. It can be seen that when the fatigue life of the bolt is $5{\times}10^6$, the value of normal amplitude fatigue limit is 167.0 MP, and when the fatigue life of the bolt is 2×10^6, the value of the allowable stress amplitude is 187.0 MP.
4. It is basically feasible to estimate the fatigue life of high-strength bolts by using the Paris formula, which can generally reflect the changing trend of fatigue life.

5. M24 twisted-shear high-strength bolts with 100% pretension force had better performance in the specified stress range. Under the 97.72% survival probability, the fatigue strength of M24 pretension force high-strength bolts was 1.86 times and 1.71 times that of the 8.8-grade M24 and 10.9-grade M24 large hexagonal head bolts, respectively.
6. By comparing the test results of M24 and M20 bolts under full pretension, it is seen that when the diameter of the bolt decreases, the fatigue strength of the bolt will reduce.

8. Future Works

In the future, this research will provide more and stronger data for further fatigue life theory analysis of other twisted-shear high-strength bolts of different diameters and grades. It is necessary that more tests on twisted-shear high-strength bolts of different diameters and grades are carried out in order to predict the fatigue life of steel structures constituted by twisted-shear high-strength bolt connections.

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Nomenclature

$\sigma_{0.2}$	measured value of the offset yield strength
σ_b	measured value of the yield strength
E	measured value of the elastic modulus
δ	measured value of elongation rate
σ_{max}	the maximum stress
σ_{min}	the minimum stress
$\Delta\sigma$	the loading stress range
σ_m	the average stress
f_y	the yield strength
R	the stress ratio (the ratio of minimum stress to maximum stress)
N	fatigue life
C	undetermined parameter
β	undetermined parameter
a_0	initial crack length
a_c	critical crack length
α	stress intensity factor
C	material parameter
m	material parameter

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