An Improved Procedure for Generating Standardised Load-time Histories for Marine Structures

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Abstract: The load sequence effect has been proved from laboratory tests to be an influencing factor that cannot be neglected in the fatigue analysis of marine structures. To take account of this significant factor, fatigue life prediction should be based on fatigue crack propagation theory rather than the currently used cumulative fatigue damage theory. Accordingly, fatigue loading needs to be provided as the load-time history in the time domain rather than the load spectrum in the frequency domain. A general procedure for generating the standardised load-time history (SLH) for marine structures based on a short-term load measurement has been proposed by the authors. This paper seeks to further improve on this procedure and explain how to apply the determined SLH in the fatigue life prediction method based on the fatigue crack propagation theory. Finally, generation and application of a SLH is given for a tubular T-joint of an offshore platform, which demonstrates the practical and effective use of the proposed approach.

Keywords: Standardised load-time history (SLH); Load sequence effect; Fatigue crack propagation; Unified fatigue life prediction (UFLP) method

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Nomenclature

a = surface crack depth (m)

c = half surface crack length (m)

$\frac{da}{dN}$ = crack growth rate (m/cycle)

A = a material- and environmentally sensitive constant of dimensions in the crack growth rate model ($MPa^{-m}m^{1-m/2}$)

m = a constant representing the slope of the corresponding fatigue crack growth rate curve in the crack growth rate model

n = an index indicating an unstable fracture in the crack growth rate model

a_0 = initial value of surface crack depth (m)

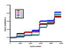
c_0 = initial value of half surface crack length (m)

$K_{\max}$ = maximum stress intensity factor ($MPa\sqrt{m}$)

$K_{\min}$ = minimum stress intensity factor ($MPa\sqrt{m}$)

 = stress intensity factor range ($MPa\sqrt{m}$)

ΔK_{th} = the threshold stress intensity factor range ($MPa\sqrt{m}$)

 = the effective stress intensity factor range ($MPa\sqrt{m}$)

K_C = the fracture toughness of the material ($MPa\sqrt{m}$)

K_{IC} = the fracture toughness of the material for plane strain ($MPa\sqrt{m}$)

K_{op} = the stress intensity factor at the opening level ($MPa\sqrt{m}$)

$K_{op}^{'}$ = the stress intensity factor at the opening level during the recovery period after overload or/and underload ($MPa\sqrt{m}$)

f_{op} = a crack opening function defined as the ratio Kop/Kmax

ϕ = the modified factor of the crack opening level

ΔK_{th0} = the threshold stress intensity factor range under zero load ratio ($MPa\sqrt{m}$)

ΔK_{effth} = the threshold effective stress intensity factor range ($MPa\sqrt{m}$)

σ_y = the yield stress of the material (MPa)

σ_u = the ultimate stress of the material (MPa)

1. Introduction

Fatigue is considered to be a main failure mode for marine structures such as ships and offshore platforms, which are mostly made of metals. Both for economic design and for safe operation, it is very important to accurately predict the fatigue crack growth process under service loading for marine structures. Although fatigue in metals and metal structures has been studied for nearly 200 years and much progress has been achieved, prediction accuracy is still not satisfactory [1]. Currently in the marine community, the widely used fatigue life prediction methods in most of the engineering standards are based on the cumulative fatigue damage (CFD) theory, which is unable to calculate the crack growth process. Furthermore, the approaches based on CFD theory have considered only a very few influencing factors in fatigue analysis, such as stress concentration and the choice of S-N curve. However, other factors, including load sequence and initial and final crack size, which have been proved from laboratory tests of similar significance, have not been taken into account. Thus, the S-N curve method cannot even explain the wide scatter of several orders of magnitude for fatigue lives of laboratory specimens [2].

Now, it is widely recognised that the next generation of fatigue life prediction methods should be based on fatigue crack propagation (FCP) theory, which can overcome the above-mentioned deficiencies of the CFD theory. Methods based on FCP theory have the potential to meet precision requirements and to explain most of phenomena observed so far. In the last decade, the authors' group has spent great efforts to develop a unified fatigue life prediction (UFLP) method for marine structures [3-10]. There are two critical issues that need to be solved for this development. One is to establish an accurate fatigue crack growth rate model that can at least explain all of the fatigue phenomena observed in laboratory tests. Through many improvements, the capabilities of the proposed crack growth rate relation were demonstrated and verified by comparing with test data from a wide range of alloys. The other is to simplify its engineering application. Engineering approaches to estimate the parameters in the improved model based on any types of existing data have also been suggested [11-13].

To apply the UFLP method for a newly designed structure, the other problem that needs to be solved is to provide a time-dependent fatigue load history that represents the fatigue loading series encountered. Furthermore, a standardised load-time history (SLH) such as the TWIST [14] and FALSTAFF [15] sequences for transport and fighter aircraft should be determined for marine structures. A general procedure for generating an SLH for marine structures based on short-term load measurements was proposed by the authors' group [16]. The present paper seeks to further improve and perfect certain steps in the proposed procedure, including establishment of an operating profile and acquisition of load samples and filtering of small load cycles. Additionally, how to apply the determined SLH in the UFLP method is explained in detail. Finally, an example is given to demonstrate the generation and application of the SLH for a tubular T-joint of an offshore platform.

2. Brief overview of the state-of-the-art of standardised load-time histories

In general, the acronym SLH is used both for ‘standardised load-time histories’ and for ‘standardised load sequences’, including ‘load spectra’ in most references, e.g., [17]. In this paper, however, SLHs are specifically defined to be standardised load-time histories, which are processes with actual time information in the time domain. For any marine structure to be designed using the UFLP method, the corresponding SLH must be provided.

It is commonly understood that SLHs do not refer to a specific design problem but comprise the typical features of the loading environment of a certain class of structures [17]. SLHs usually do not cover all of the load cycles within the total anticipated service life but only a representative fraction (return period). They are thought to be repeated in a fatigue test or a numerical simulation until final failure occurs or the anticipated usage is safely covered. Although realistic load sequences that structures experience during their service life can be taken into consideration, calculation time and testing cost can be greatly reduced by applying the same SLH to a class of structures or similar components.

Due to the above-mentioned advantages, SLHs have been developed and applied to fatigue studies for about 40 years. The first proposed SLH was Gassner’s eight-level blocked programme test, which can be dated back to the 1930s [18, 19]. With its need for optimum lightweight design, the aircraft industry was originally the main driver behind the significant progress of SLHs in the 1970s. Two of the most well-known SLHs are the TWIST [14] and FALSTAFF [15] sequences for transport and fighter aircraft, respectively, which have been and are still applied in numerous studies on materials, joints and other structural elements. In the same period, GAUSSIAN [20] was presented for general application for fatigue tests by Haibach et al. HELIX/ FELIX [21] and the two TURBISTAN [22, 23] sequences are further examples from the aerospace field. Due to the relatively high cycle numbers of the TWIST and HELIX/FELIX sequences, shortened versions of these SLHs have also been devised, such as WISPER [24], MINITWIST [25] and others.

Starting in the mid-1980s, SLHs have been developed for automobiles, offshore platforms and steel mill drives, for example. In the US, activities were mainly centred on the derivation of test load sequences to be used for evaluation and development of fatigue life prediction methodology [26]. In 1977, a series of short sequences, such as Transmission, Suspension and Bracket [27], were published by the SAE Fatigue and Evaluation Committee. These were more realistic with regard to spectrum length and distribution of small and large cycles. Since 1990, the CARLOS series of SLHs have been presented in automotive applications, including CARLOS multi [28], CARLOS PTM [29], CARLOS PTA [30] and CARLOS TC. With respect to marine structures, WASHI [31, 32] was developed by an international working group for typical drag-dominated smaller members of platforms operating in the North Sea or similar sites. In addition, Japanese researchers proposed a random loading model to simulate real encountered wave conditions, called the ‘storm model’ [33]. It is also a simplified standardised loading model for the fatigue strength analysis of offshore structures. In recent years, the authors’ group has conducted research on SLHs of marine structures [16, 34, 35].

3. Generation of SLHs for marine structures

In general, the determination of SLHs for marine structures is more difficult than for aircraft or automobiles. Marine structures experience a more complex loading environment during their long-term service life, including forces from wind, wave, current and others. There are many approaches for determining SLHs for marine structures. In this paper, a generation approach is presented based on a short-term load sample, which is easy to acquire in most practical applications. The general procedure is shown in Fig. 1 and further steps will be addressed in detail in the following sections.

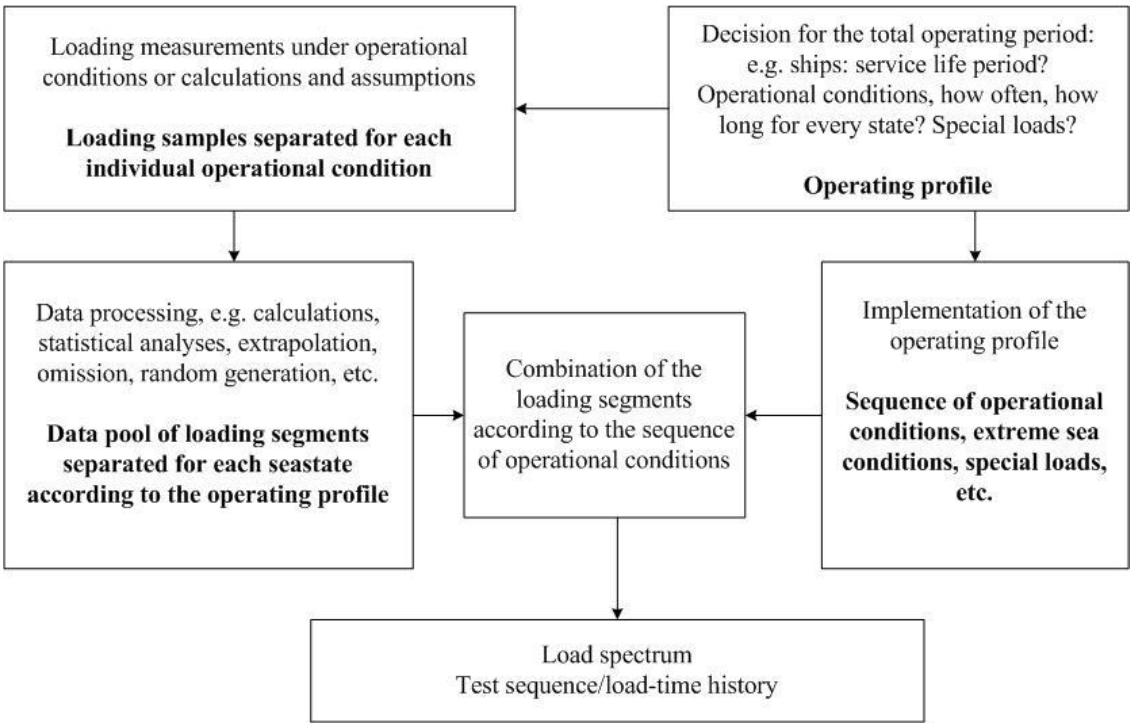
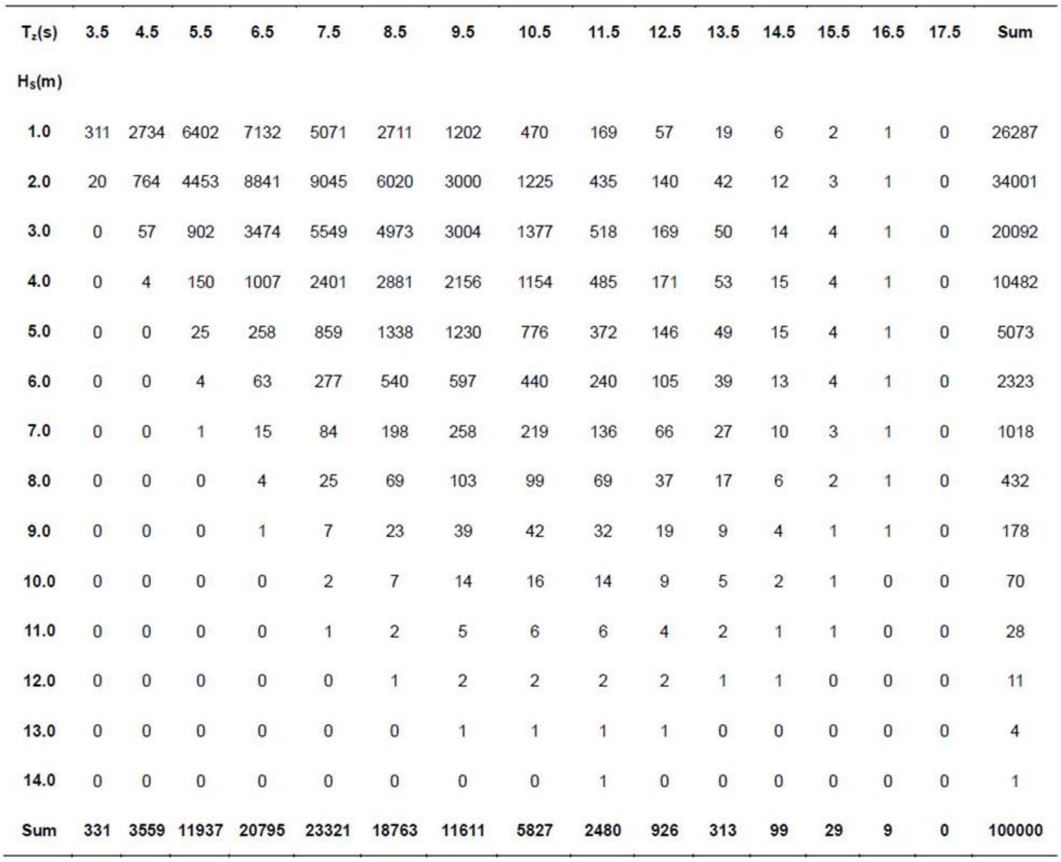


Fig. 1. General approach for the generation of SLHs (example: ships)

3.1. Operating profiles

The operating profile describes the service conditions for the total or a representative fraction of the operating period. For offshore structures, the loading environment can be described as seastates with different levels, which are commonly ranked according to the significant wave height (H_s) and wave period (T). The most commonly used form to describe the distribution characteristics in a sea region is the scatter diagram, as shown in Fig. 2. According to statistical data in the scatter diagram, the occurrence probability of each seastate can be estimated. The scatter diagram can often be used to analyse the loading environment of offshore platforms, which work in a fixed location during their entire service life or for a relatively long period.



T_z(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	Sum
H_s(m)																
1.0	311	2734	6402	7132	5071	2711	1202	470	169	57	19	6	2	1	0	26287
2.0	20	764	4453	8841	9045	6020	3000	1225	435	140	42	12	3	1	0	34001
3.0	0	57	902	3474	5549	4973	3004	1377	518	169	50	14	4	1	0	20092
4.0	0	4	150	1007	2401	2881	2156	1154	485	171	53	15	4	1	0	10482
5.0	0	0	25	258	859	1338	1230	776	372	146	49	15	4	1	0	5073
6.0	0	0	4	63	277	540	597	440	240	105	39	13	4	1	0	2323
7.0	0	0	1	15	84	198	258	219	136	66	27	10	3	1	0	1018
8.0	0	0	0	4	25	69	103	99	69	37	17	6	2	1	0	432
9.0	0	0	0	1	7	23	39	42	32	19	9	4	1	1	0	178
10.0	0	0	0	0	2	7	14	16	14	9	5	2	1	0	0	70
11.0	0	0	0	0	1	2	5	6	6	4	2	1	1	0	0	28
12.0	0	0	0	0	0	1	2	2	2	2	1	1	0	0	0	11
13.0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	4
14.0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Sum	**331**	**3559**	**11937**	**20795**	**23321**	**18763**	**11611**	**5827**	**2480**	**926**	**313**	**99**	**29**	**9**	**0**	**100000**

Fig. 2. Scatter diagram for worldwide trade [36]

Unlike offshore platforms, which generally work in a relatively fixed location, ships frequently sail along given routes during their service period. The long-term observed data of wave conditions should be collected and statistically analysed for the specified route to establish the operating profile. For different sail phases of a ship, distinct patterns of grouped load cycles often can be distinguished, called a loading event. The occurrence of loading events must be defined in terms of frequency, severity and sequence, which in summary constitute the operating profile for ships.

3.2. Load measurements

As a basic input to the generation of a new SLH, statistically adequate samples of load measurements under operational conditions must be available for every load case, e.g., for ships, load measurements under every seastate should be provided. These samples are commonly acquired by in-service measurements from several similar structures. The current widely used measurement technologies are based on strain gauges, fibre grating and others. Recent developments in reliability-based inspection and hull condition monitoring have been of great help in acquiring accurate load samples over a long period.

However, if experimental conditions cannot be satisfied or measurement data are limited, the load samples can also be obtained by direct calculation or simple assumption. In the fatigue analysis of marine structures, long-term distribution of wave-induced stress range can be described by the two-parameter Weibull distribution, the probability density function of which is expressed as follows:

$$f_s(S)=\frac{h}{q}\left(\frac{S}{q}\right)^{h-1}\exp\left[-\left(\frac{S}{q}\right)^{h}\right],0\le S<+\infty, \tag{1}$$

where S is the stress range and h and q are the shape parameter and scale parameter, respectively. Fig. 3 gives an example of a stress history generation that follows the Weibull distribution.

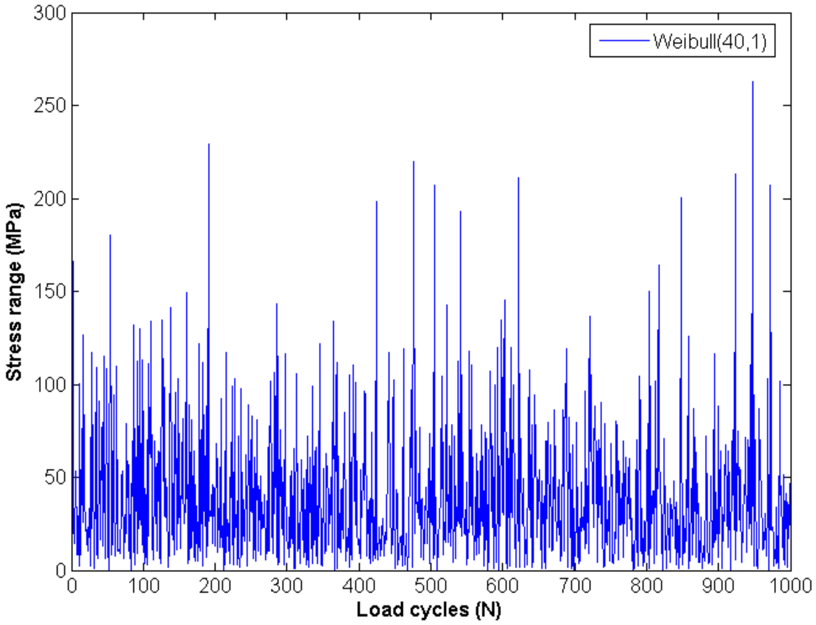


Fig. 3. A sample of random fatigue loading generated with the given parameters

A long-term wave-induced stress history can also be regarded as a series of short-term load histories that follow a Rayleigh distribution. Similarly, the short-term load samples under every seastate can be simulated through a probability density function with the given parameters.

3.3. Data processing

When load samples for each individual operational condition are available, further data processing is always needed. This often includes selection of return period length, omission of small load cycles and extrapolation of short-term load samples.

As mentioned in section 2, SLHs cover a representative fraction of load history rather than the total service period. It is therefore critical to select the length of the SLH, which is also called the return period. It must be repeated several times until failure occurs, otherwise, the full variety of load amplitudes is not contained in the SLH in their correct percentages. However, too short of a return period means that infrequent but high load amplitudes are not contained in the load history, although they do occur in service and will greatly affect fatigue life [32]. Thus, the load history applied in tests or calculations is quite different from that in service. In general, the design life of offshore structures is designated as 20~25 years, and one year seems to be an appropriate selection for return period length because structures experience similar weather conditions every year, especially offshore platforms with relatively fixed working locations. Additionally, experts have suggested that the highest stress amplitude in the load history should occur not less than 10 times before failure [37].

Whether the load samples are acquired by measurement or simulation, there is inevitably a certain amount of small load oscillations contained in the load histories, which are often considered to have little effect on the fatigue damage of marine structures. To improve the calculation efficiency and minimise the test time, these small load cycles should be omitted. However, ‘allowable’ filter levels for omission have to be defined with care. Based on FCP theory, the stress intensity factor range ΔK (or the effective stress intensity factor range ΔK_{eff} in some methods) is viewed as the driving force of crack propagation to determine if the crack grows under load cycles. Theoretically, if ΔK is lower than ΔK_{th} (where ΔK_{th} is the threshold stress intensity factor range), the fatigue crack cannot propagate. These load cycles that cannot lead to crack propagation can be filtered. Some experience-based recommendations on the selection of filter levels have been given in some references [38, 39]. For example, the filtering threshold can be set to 5%~10% of the maximum load range in most cases.

After filtering small load cycles, the next step is necessary when load samples for some seastates are too short to contain all of the load cycles occurring in the return period. This is the most common case in practical applications. Short-term load samples should be extrapolated to the appropriate length, which is again dependent on the operating profile of the specified structure. The extrapolation method used in this paper is the so-called peaks-over-threshold (POT) technique proposed by Johannesson [40]. The main idea of this method is to repeat the measured load block but to modify the highest maxima and lowest minima in each block. The random regeneration of each block is based on statistical extreme value theory. The detailed procedure is described in Ref [41].

3.4. Random reconstruction

Referring to the method introduced in Ref [33], for marine structures in any sailing route or operating site, all of the load histories that are processed with the above procedures can be divided into two kinds of seastates: storm sea and calm sea. Under storm sea conditions, the occurrence of waves is a time-dependent process. Wave height increases over time, reaches a maximum value at one point only, then begins to decrease gradually, as shown in Fig. 4.

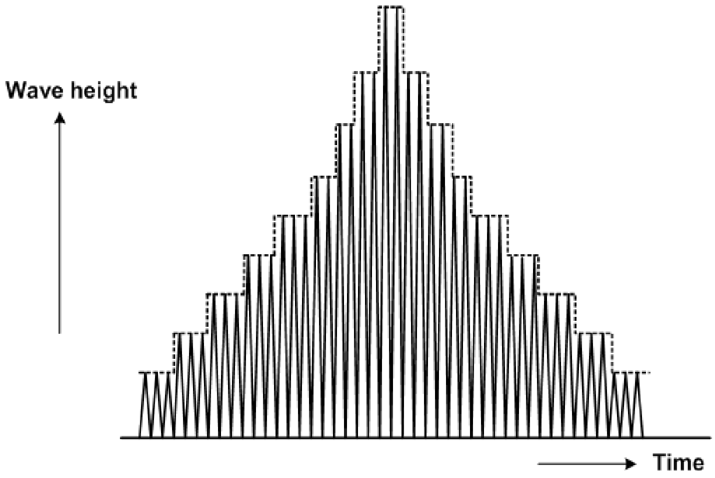


Fig. 4. Loading pattern in a storm [33]

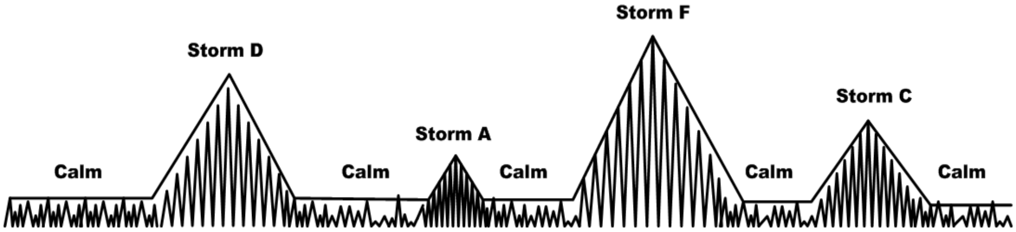


Fig. 5. Simplified random loading model for fatigue strength analysis of ship structural members [33]

The observed data in Ref. [33] showed that the tendency of wave-induced stress was the same as the ‘storm model’. In calm sea conditions, the occurrence of waves is a time-independent process, as shown in Fig. 5. These two kinds of sea conditions appear in random order. Consequently, a load-time history with the length of the return period can be composed in various sequences. In some cases, a logical sequence of load cycles can be decided upon, for example, that a voyage of a ship begins with a load draught, followed by sailing in ballast and so on. According to the severity of fatigue behaviour predicted by the UFLP method, the SLH of the designed structure will be finally determined.

4. Application of SLHs in the unified fatigue life prediction method

The UFLP method, which is based on the FCP theory, has been proposed and developed by the authors’ group over the last 10 years [4-13]. The crack size is calculated on a cycle-by-cycle basis and the fatigue loading must be provided as a load-time history rather than as a load spectrum. Fig. 6 shows the general procedure of the UFLP method.

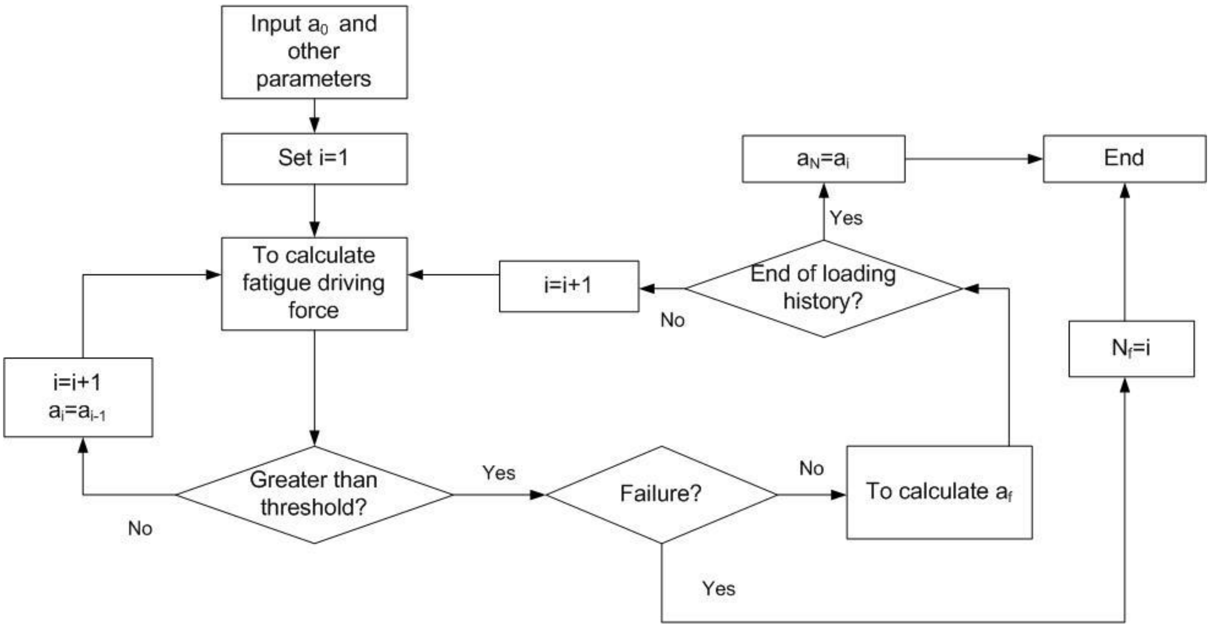


Fig.6. The general procedure of the UFLP method [8]

The determined SLH can be repeated as a fatigue loading series to calculate the crack size cycle by cycle until final failure occurs. The total crack size can be mathematically represented in Eq. (2):

$$a = a_0 + \sum_{i=1}^{N} \Delta a_i \quad . \tag{2}$$

Many studies have shown that prediction data from the crack growth rate model proposed in the UFLP method agree well with test data on a wide range of alloys under both constant-amplitude loading and variable-amplitude loading [9,10]. The improved crack growth rate model under variable-amplitude loading can be written in the following form:

$$\frac{da}{dN} = \frac{AM^{m}}{1-\left(K_{\max}/K_C\right)^{n}} , \tag{3}$$

$$M = K_{\max} - K_{op}^{'} - \Delta K_{effth} , \tag{4}$$

$$K_{op}^{'} = \Phi K_{op} = \Phi f_{op} K_{\max} , \tag{5}$$

where Φ is the modified factor of the crack opening level and its expression varies with the different loading modes. More information on the above crack growth rate model can be obtained from the respective references [8-10].

Fig. 7 displays the fatigue life calculation procedure using the improved crack growth rate model presented in the UFLP method. Detailed information, such as the final crack size and fatigue life of the designed offshore structure, is outputted as fatigue assessment results. However, if the designed service life of the structure is reached but the fatigue limit is not exceeded, this crack should be regarded as acceptable and the final crack size will also be obtained.

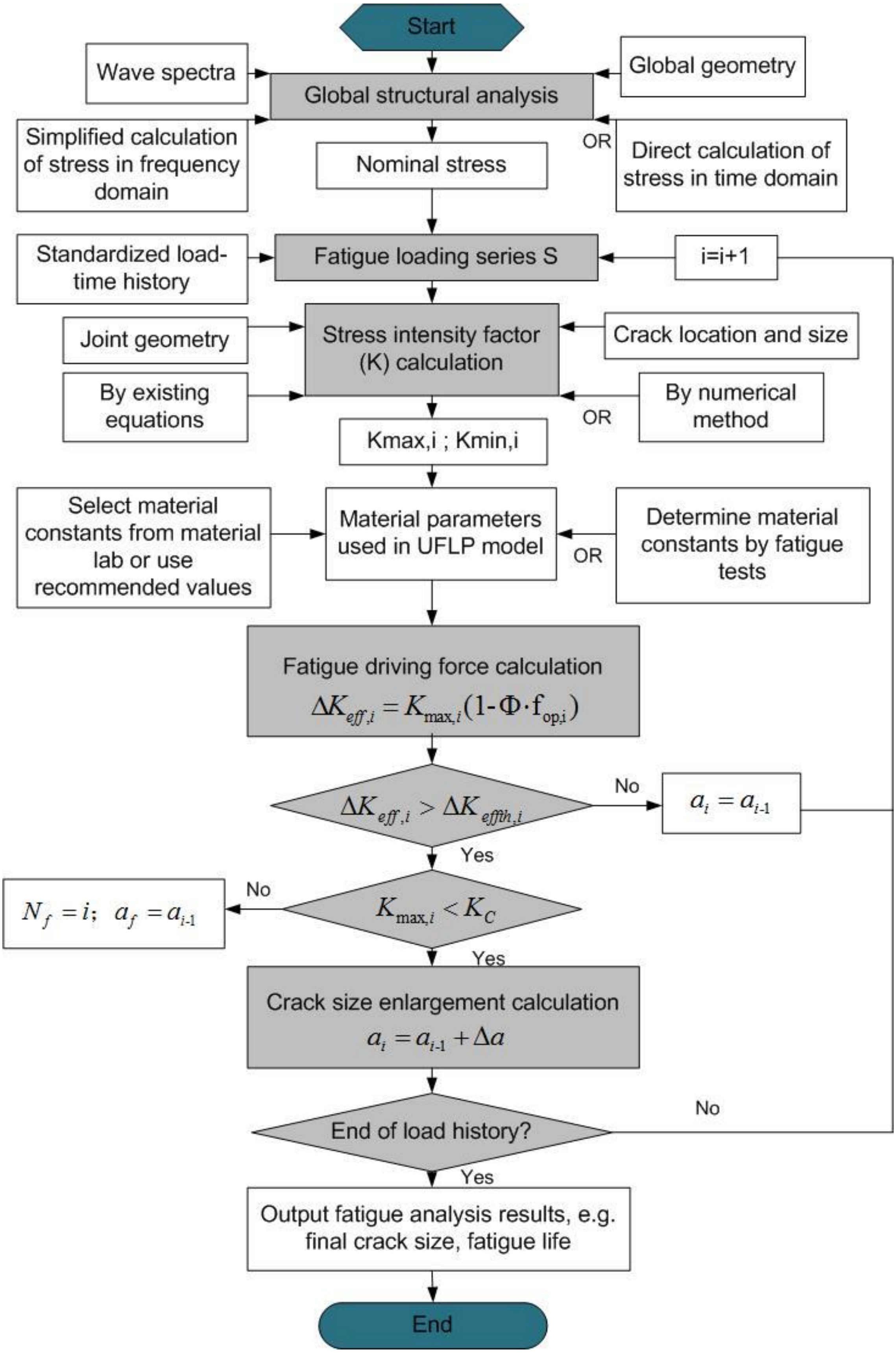


Fig. 7. Flow diagram for the fatigue life calculation procedure of the UFLP model

5. Applied example

An example of the determination and application of the SLH for a T-joint is given in this section. The T-joint is the simplest type of steel tubular joint and is widely used in offshore platforms. The geometry of the joint is shown in Fig. 8. Much experimental data have indicated that, in most cases, the fatigue hot spot is located at the saddle point of a T-joint under brace tension. Therefore, a surface crack is simulated at the saddle point of a T-joint for fatigue strength analysis in this paper, as shown in Fig. 9.

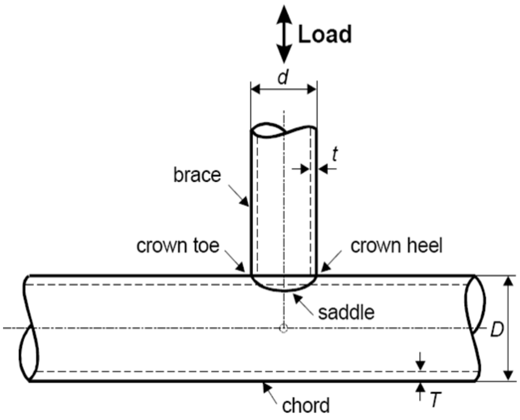


Fig. 8. T-joint model

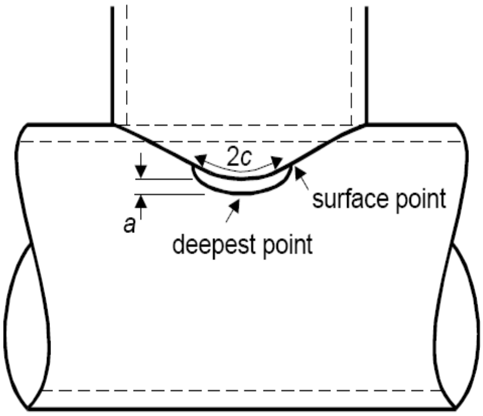


Fig. 9. Surface crack at the saddle point of a T-joint

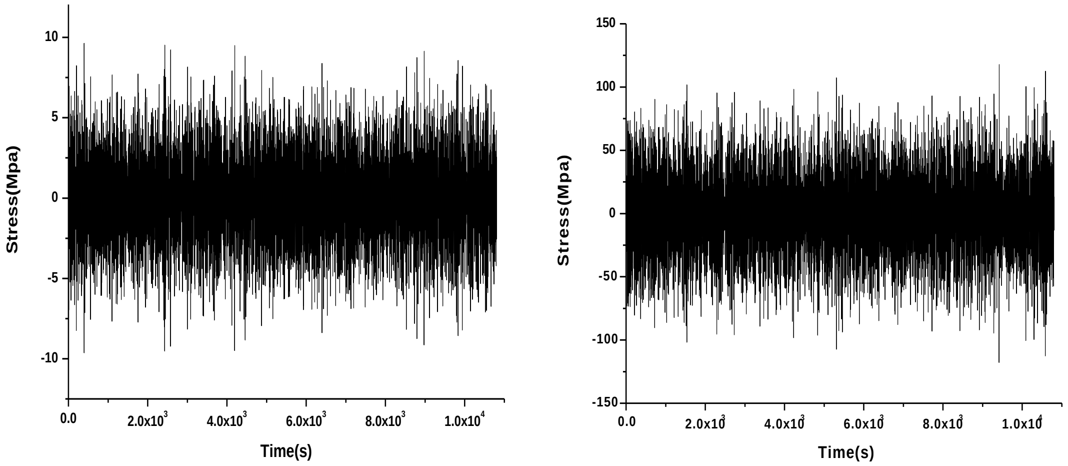
Regarding the operating profile for an offshore platform, the wave scatter diagram in the North Atlantic [36] is used for long-term environmental statistics, as shown in Table 1. The occurrence probability of each seastate can be estimated. To simplify the calculation, the five highest seastates 12~16 are combined into one seastate as they occur infrequently.

Table 1. Scatter diagram for the North Atlantic [36]

T_z(s) **H_S(m)**	**3.5**	**4.5**	**5.5**	**6.5**	**7.5**	**8.5**	**9.5**	**10.5**	**11.5**	**12.5**	**13.5**	**14.5**	**15.5**	**16.5**	**17.5**	**Sum**
1.0	0	72	1416	4594	4937	2590	839	195	36	5	1	0	0	0	0	14685
2.0	0	5	356	3299	8001	8022	4393	1571	414	87	16	3	0	0	0	26167
3.0	0	0	62	1084	4428	6920	5567	2791	993	274	63	12	2	0	0	22196
4.0	0	0	12	318	1898	4126	4440	2889	1301	445	124	30	6	1	0	15590
5.0	0	0	2	89	721	2039	2772	2225	1212	494	162	45	11	2	1	9775
6.0	0	0	1	25	254	896	1482	1418	907	428	160	50	14	3	1	5639
7.0	0	0	0	7	85	363	709	791	580	311	131	46	14	4	1	3042
8.0	0	0	0	2	27	138	312	398	330	197	92	35	12	3	1	1547
9.0	0	0	0	1	8	50	128	184	171	113	58	24	9	3	1	750
10.0	0	0	0	0	3	17	50	80	82	59	33	15	6	2	1	348

11.0	0	0	0	0	1	6	18	33	37	29	17	8	3	1	0	153
12.0	0	0	0	0	0	2	7	13	15	13	8	4	2	1	0	65
13.0	0	0	0	0	0	1	2	5	6	6	4	2	1	0	0	27
14.0	0	0	0	0	0	0	1	2	2	2	2	1	1	0	0	11
15.0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	4
16.0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Sum	**0**	**77**	**1849**	**9419**	**20363**	**25170**	**20720**	**12596**	**6087**	**2465**	**872**	**275**	**81**	**20**	**6**	**100000**

Due to the lack of observed data here, short-term stress histories of each seastate are obtained by random data generation. Generally, the short-term probability distribution of wave-induced stress can be approximately described by the Rayleigh distribution. Fig. 10 gives demonstrations of wave-induced stress histories of seastate 1 and seastate 12 over 3 hours. Stress histories of other seastates are acquired in the same way.



(a) Seastate 1

(b) Seastate 12

Fig. 10. Randomly generated wave-induced stress histories of about 3 hours duration

A reasonable length for the return period is one year for tubular T-joints because an offshore platform mostly experiences the similar environment in its location every year. The total number of load cycles for one year is 5×10^6 (10^8/20 years), so the mean wave period is about 6.3 s (1 year×365 days×24 h×3600 s/5×10^6). The load cycle number of each seastate during the return period can be calculated, as shown in Table 2.

Table 2. Load cycle number of each seastate during one year

Seastates used in this paper	Hs (m)	Probability of occurrence	Load cycle number in one year (N)
Seastate 1	1	0.14685	734250

Seastate 2	2	0.26167	1308350
Seastate 3	3	0.22196	1109800
Seastate 4	4	0.1559	779500
Seastate 5	5	0.09775	488750
Seastate 6	6	0.05639	281950
Seastate 7	7	0.03042	152100
Seastate 8	8	0.01547	77350
Seastate 9	9	0.0075	37500
Seastate 10	10	0.00348	17400
Seastate 11	11	0.00153	7650
Seastate 12	>=12	0.00108	5400
Total	—	1	5×10^6

Next, by the POT extrapolation method [40, 41], the short-term stress histories of all 12 seastates can be extrapolated to the corresponding cycle number as listed in Table 2. To improve the calculation efficiency, the small load cycles that do not largely influence the structural fatigue strength should be removed before extrapolation. In this section, the filtering threshold is set to 5% of the maximum load range. Fig. 11 shows the filtration and extrapolation of short-term stress histories of seastate 12. Short-term stress samples of other seastates can be processed using the same method. The load cycles of all 12 seastates in one year can then be obtained.

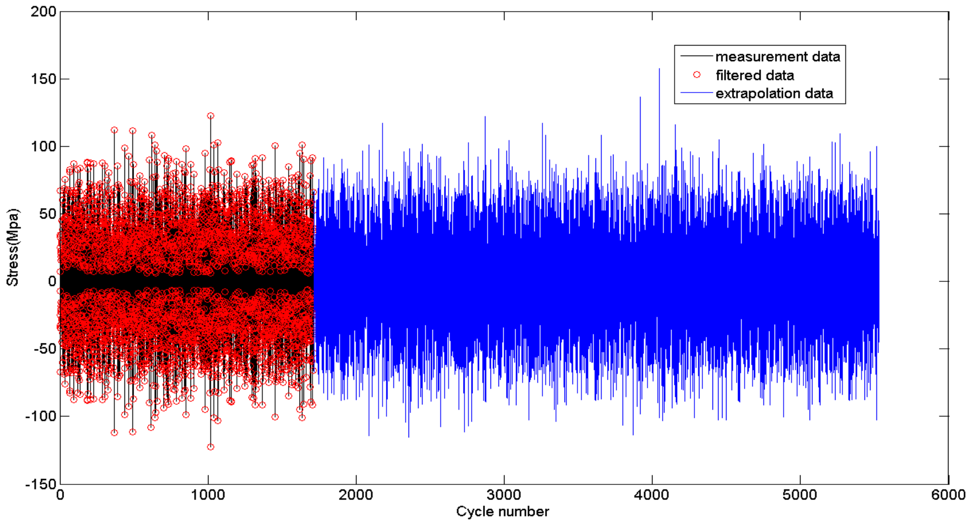
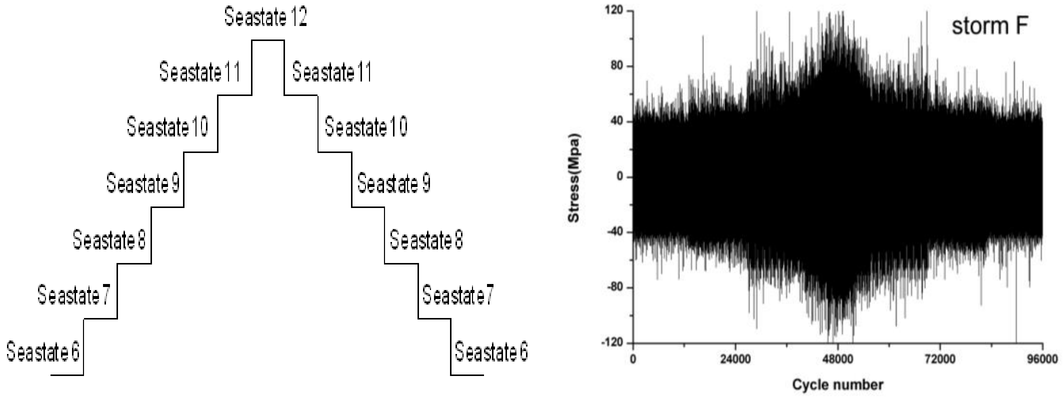


Fig. 11. Filtration and extrapolation of short-term wave-induced stress of seastate 12

Consequently, all 12 seastates are divided into two classes: calm sea (from seastate 1 to seastate 5) and storm sea (from seastate 6 to seastate 12). The storm sea condition can also be classified into six types of storms according to the maximum seastate level in each storm, A (seastate 7), B (seastate 8), C (seastate 9), D (seastate 10), E (seastate 11) and F (seastate 12). A sketch of storm F is shown in Fig. 12 (a).

The total probability of occurrences of storm sea conditions is 0.11587 according to the data in Table 2. In other words, there are about 42 days of storm sea conditions within one year. Assume that the storm number of each type is A (1), B (1), C (1), D (1), E (1) and F (1), so the mean value of each storm duration is about 7 days. The load cycle number in each storm is 96000 (7 days×24 h×3600 s/6.3 s), as shown in Fig. 12 (b).



(a) Illustration of storm F (b) Load cycles in storm F

Fig. 12. Loading pattern in storm F

The material property parameters used in the UFLP model are given in Table 3. For the surface crack at the saddle point of the T-joint, stress intensity factor K can be calculated according to the parametric formulae proposed by Rhee et al. [42]. Geometric dimensions of the tubular T-joint are detailed in Table 4. These values lie well within the validity ranges of the equations of Rhee et al.

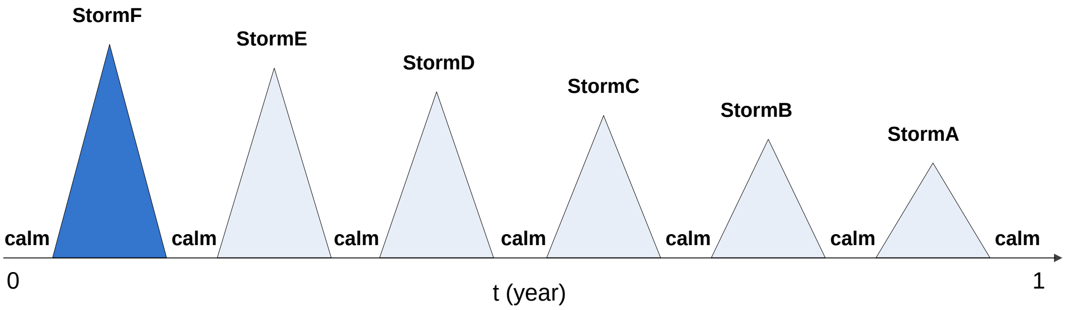
Table 3. Material parameters used in the improved crack growth rate model

Parameter	Value
A（$MPa^{-m}m^{1-m/2}$）	2.737 E-9
m	1.349
n	6.0
r_e（m）	1E-6
K_{IC}（$MPa\sqrt{m}$）	150.0
ΔK_{th0}（$MPa\sqrt{m}$）	13.2
σ_u（MPa）	980
σ_y（MPa）	800

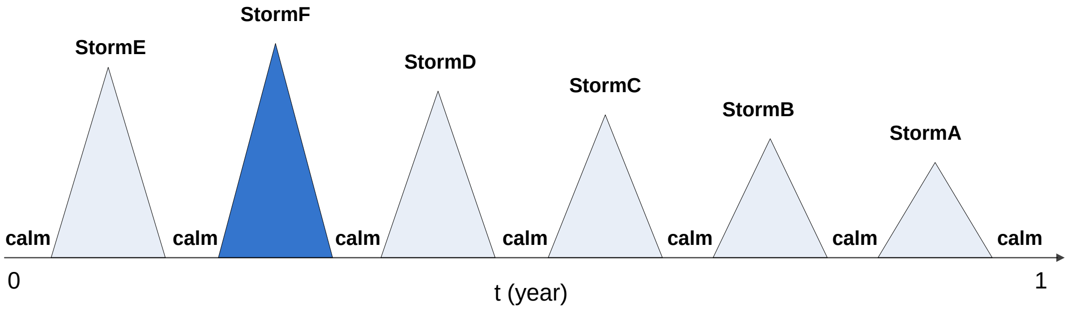
Table 4. Dimensions and initial surface crack sizes of the tubular T-joint

Parameter	**Value (mm)**
D	914.56
d	457.28
T	32
t	16
L	5486.4
a_0	3.5
c_0	10

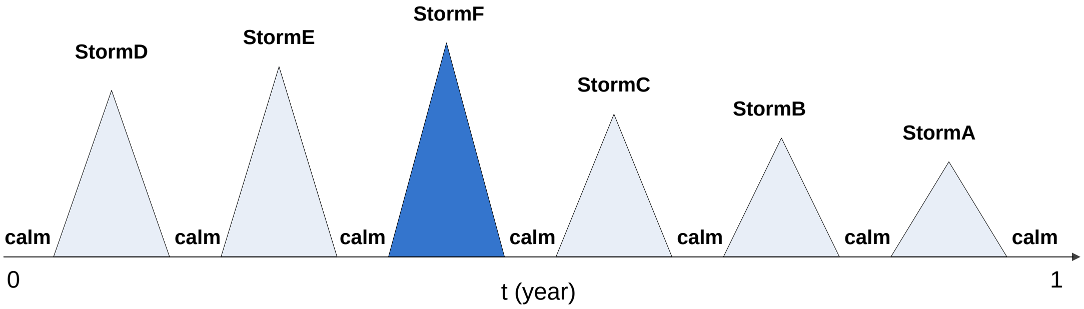
The last step is to rearrange the positions of all of the storms within one year. First, change the position of storm F from the 1st to the 6th position, as shown in Fig. 13 (a)-(f). The simulation results of crack depth (a) versus load cycles (N) under the six load modes are shown in Fig. 14, where the number behind F indicates the position of storm F in the overall load history (the same as below).



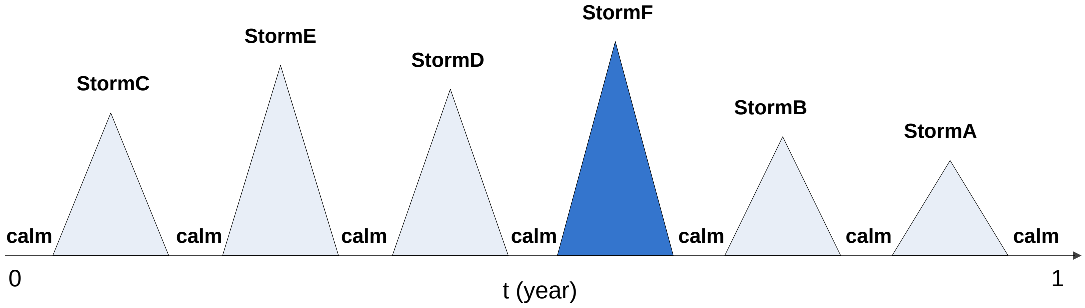
(a) Storm F lies in the 1st position



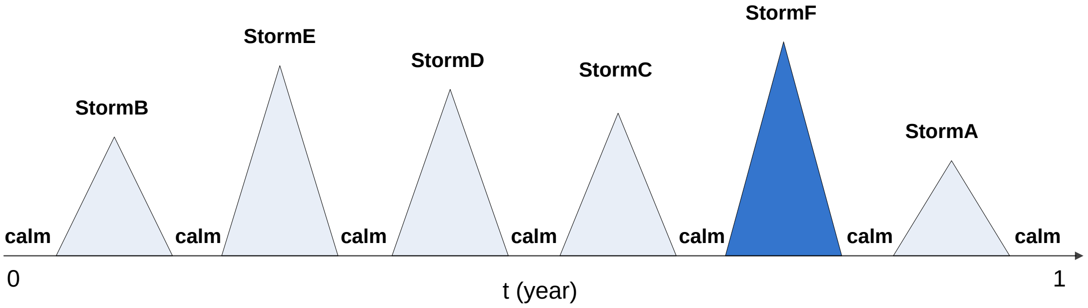
(b) Storm F lies in the 2nd position



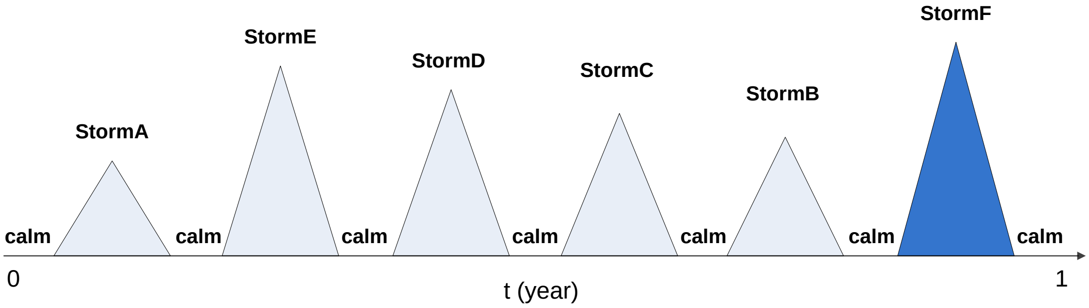
(c) Storm F lies in the 3rd position



(d) Storm F lies in the 4th position



(e) Storm F lies in the 5th position



(f) Storm F lies in the 6th position

Fig. 13. Different load modes obtained by changing the position of storm F

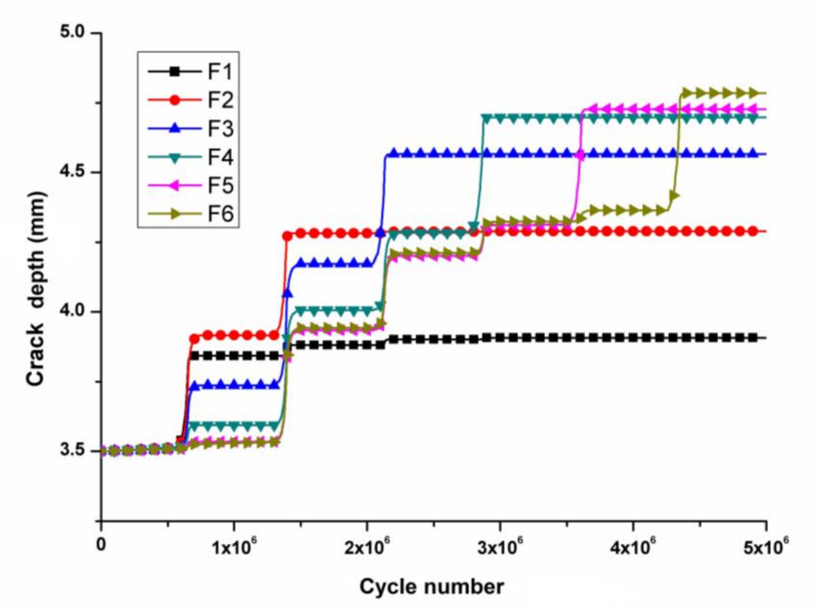


Fig. 14. Predicted a-N curves under the six types of load modes in Fig. 13

The fatigue growth behaviour of the tubular T-joint is sensitive to the load sequence effect. The crack growth rate is much greater under storm sea conditions than that under calm sea conditions. For the different storms that are of the same load cycle number, the higher the storm level, the faster the crack propagates. However, after a severe storm occurs, e.g., storm F, retardation due to overloading has a large effect on the crack growth rate. In the comparison of the fatigue crack propagation results, load case (F6) is the most serious condition, so the position of storm F is determined at the 6th position (see Fig. 15). If storm E is moved in the same manner as storm F, similar results can be obtained, as in Fig. 16. The position of storm E is determined to be the 4th position, as shown in Fig. 17 (a).

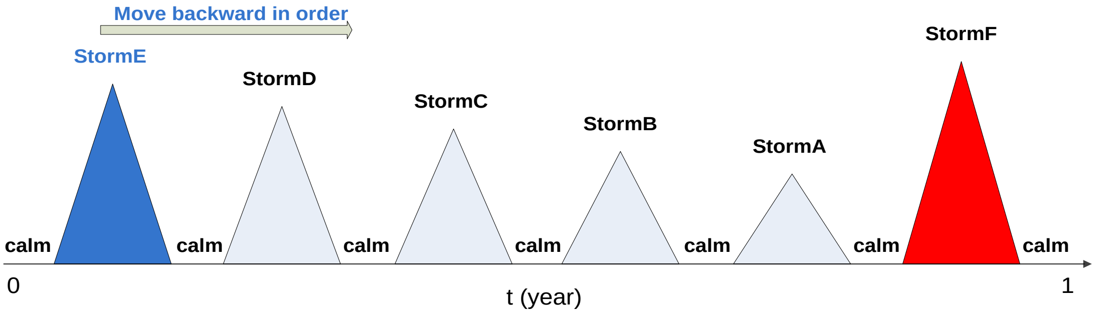


Fig. 15. Determination of the position of storm F and movement of storm E

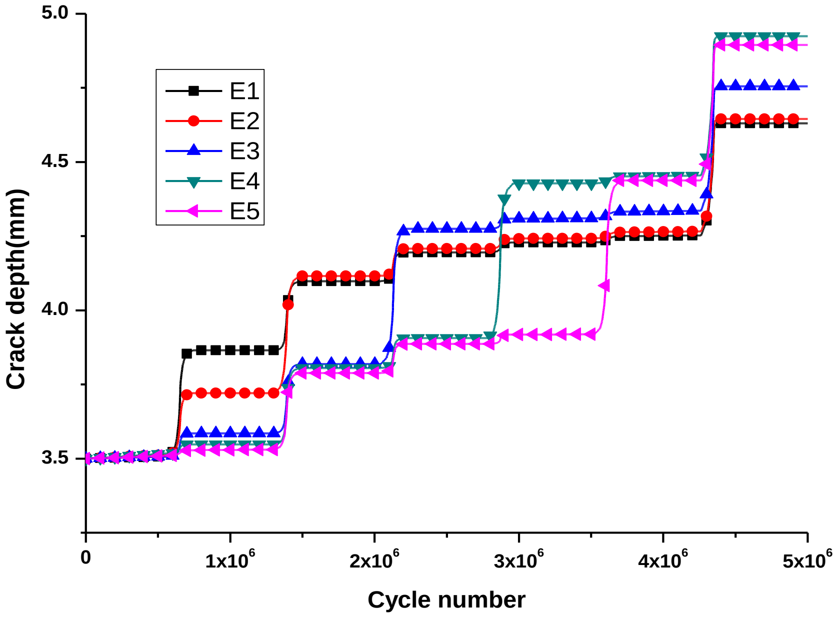
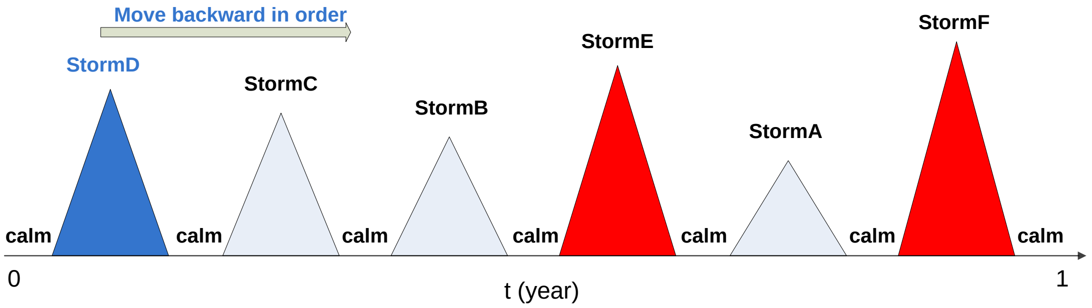
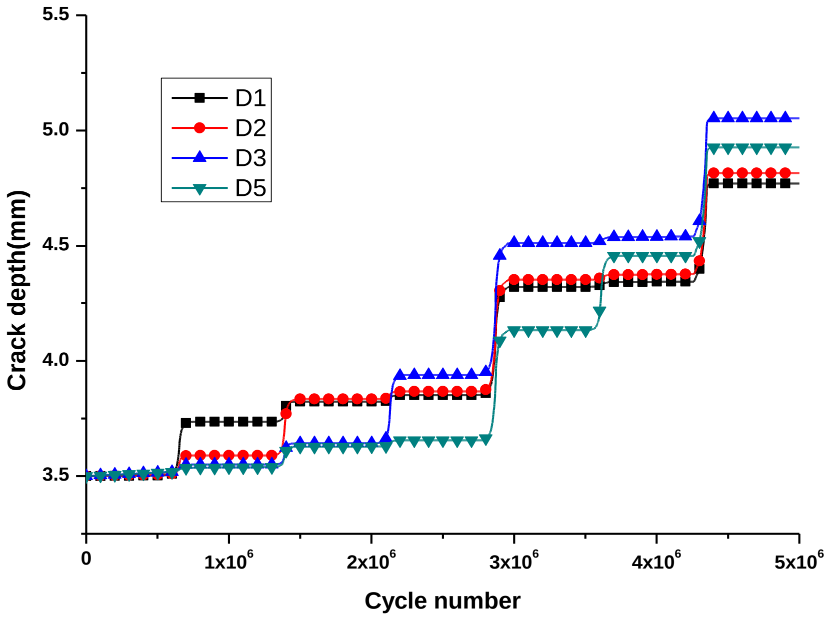


Fig. 16. Predicted a-N curves under five load modes by changing the position of storm E

Similarly, Fig. 17 (a)-Fig. 19 (a) display the procedures for determining the positions of storm D, storm C and storm B, and Fig. 17 (b)-Fig. 19 (b) show the a-N curves under the corresponding load modes, respectively. Finally, the SLH of the tubular T-joint is generated after determining the positions of all of the storms, as in Fig. 20.

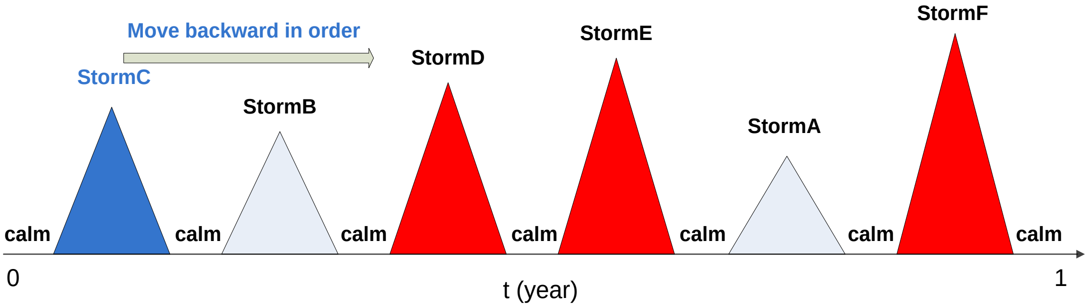


(a) Determination of the position of storm E and movement of storm D

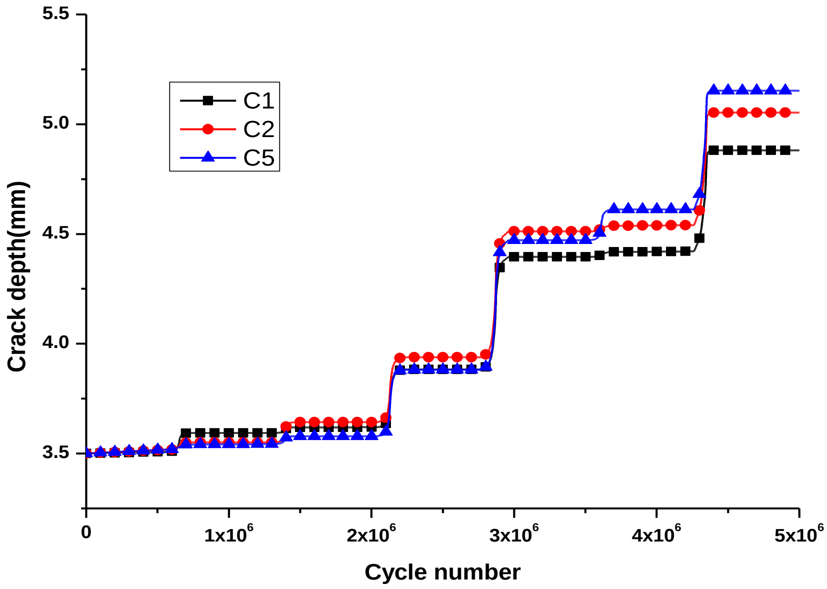


(b) Predicted a-N curves under four load modes by moving storm D

Fig. 17. Load modes and predicted results

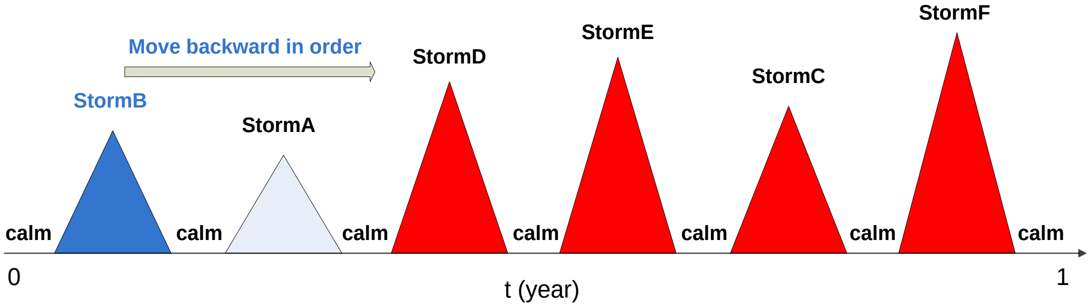


(a) Determination of the position of storm D and movement of storm C

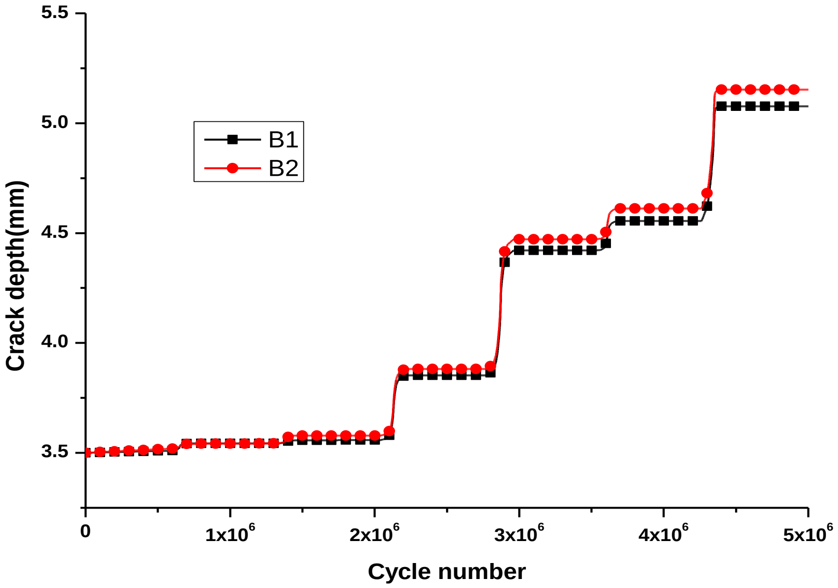


(b) Predicted a-N curves under three load modes by moving storm C

Fig. 18. Load modes and predicted results



(a) Determination of the position of storm C and movement of storm B



(b) Predicted a-N curves under two load modes by moving storm B

Fig. 19. Load modes and predicted results

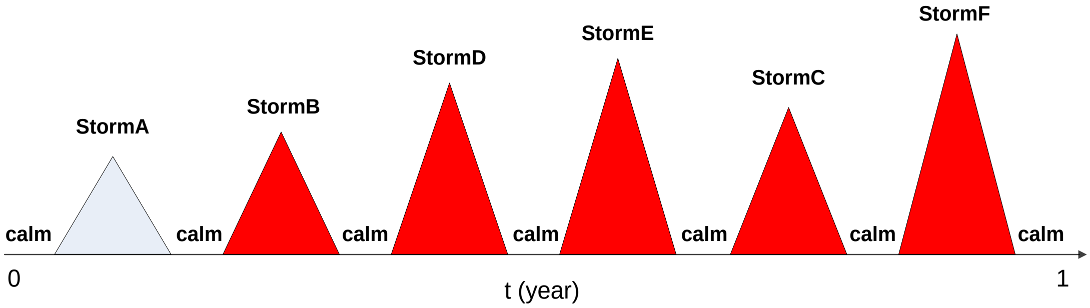


Fig. 20. The final determination of the standardised load-time history

Assuming that the designed service life of an offshore platform is 20 years, the one-year SLH can be repeated 20 times as a fatigue loading series in the UFLP method. The fatigue life prediction result is shown in Fig. 21. The surface crack at the saddle point of the T-joint grows steadily within 20 years, so this crack can be regarded as an acceptable flaw during the designed life of the offshore platform.

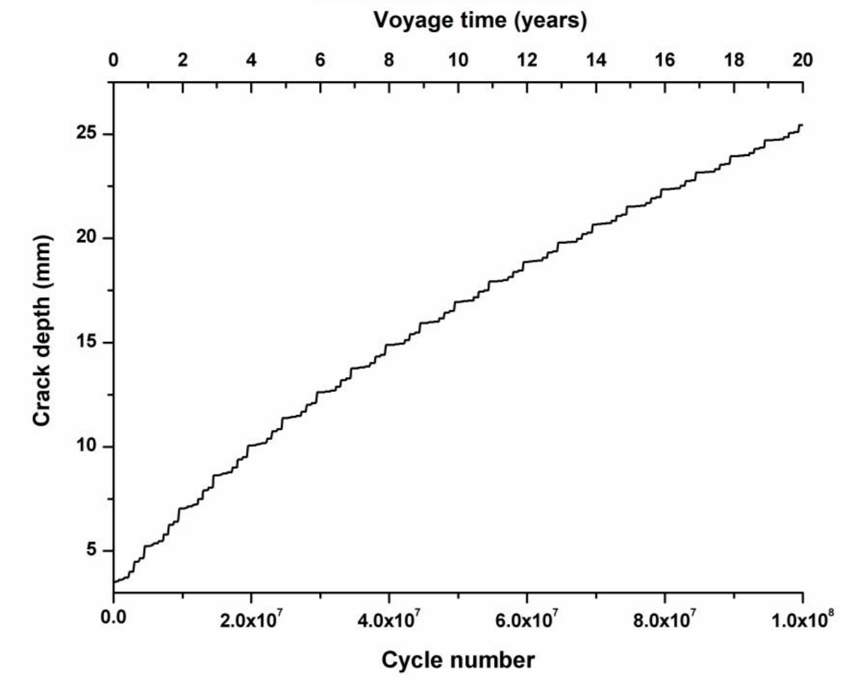


Fig. 21. Fatigue life prediction result of the T-joint using the determined SLH

6. Concluding remarks

Marine structures are mostly made of metals and experience variable-amplitude loading during their long-term service life. Their fatigue crack growth behaviour have been shown in laboratory tests to be very sensitive to load sequence effect. To account for the important influencing factors, fatigue life prediction methods should be based on FCP theory rather than the currently used CFD theory. Accordingly, fatigue loading needs to be provided as the load-time history with actual load sequence in the time domain rather than the load spectrum in the frequency domain. SLHs provide an appropriate selection of load sequences for this purpose and a series of advantages for applying SLHs in fatigue issues have been realised. Based on this background, a general procedure for determining the SLH for marine structures has recently been developed by the authors' group. In this paper, further improvements in certain steps of this procedure are made, including the establishment of an operating profile, acquisition of load samples and filtering of small load cycles. In addition, how to apply the determined SLH in the UFLP method, which is based on the FCP theory, is explained in detail. Finally, an example is given to demonstrate the generation and application of the SLH for a tubular T-joint of an offshore platform. Through these analyses, the following conclusions can be drawn:

(1) Retardation of crack growth due to overloading can be clearly seen from the fatigue analysis results. When high-level storms occur earlier in the overall load history, the final crack size is generally smaller than the crack size when they occur later. It can thus be concluded that earlier occurrences of high-level storms are helpful in slowing the rate of crack growth and prolonging the fatigue life of offshore structures. However, it must be pointed out that this conclusion is only qualitative and must be further validated by test data. Undoubtedly, load sequence effects greatly affect the behaviour of crack growth and cannot be neglected in the assessment of the fatigue strength of marine structures.

(2) The determined SLH can be applied as a fatigue loading series to calculate the crack size cycle

by cycle in FCP theory-based methods, e.g. the UFLP method in this paper. It is repeated until final failure occurs or the expected service life is reached. It not only takes into account the realistic load sequences encountered but also greatly saves time in numerical simulations. Even though it is presently difficult to verify the reliability of the fatigue analysis results obtained using SLHs, it would indeed be an intriguing update of the Classification Rules and fatigue assessment procedures and would lead to the safe reduction of scantlings and cost.

(3) Finally, it is necessary to point out that the determination of an SLH for marine structures is not a purely theoretical problem but is actually a decision-making problem. The actual determination of a SLH for a particular type of offshore structure is the responsibility of classification societies and requires cooperative effort from international authorities and related laboratories in different countries.

Acknowledgments

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References

[1] Fricke, W., Cui, W.C., Kierkegaard, H., Kihl, D., Koval, M., Lee, H.L., Mikkola, T., Parmentier, G., Toyosada, M., Yoon, J.H. Comparative fatigue strength assessment of a structural detail in a containership using various approaches of classification societies, Marine Structures 2002, 15(1):1-13.

[2] Hanaki, S., Yamashita, M., Uchida, H., Zako, M. On stochastic evaluation of S–N data based on fatigue strength distribution, International Journal of Fatigue 2010, 32:605-609.

[3] Cui, W.C. A state-of-the-art review on fatigue life prediction methods for metal structures. Journal of Marine Science and Technology 2002, 7(1):43-56.

[4] Cui, W.C. A feasible study of fatigue life prediction for marine structures based on crack propagation analysis. Journal of Engineering for the Maritime Environment 2003, 217(5):11-23.

[5] Cui, W.C., Huang, X.P. A general constitutive relation for fatigue crack growth analysis of metal structures. Acta Metallurgica Sinica 2003, 16(5):342-354.

[6] Wang, Y.F., Cui, W.C., Wu X.Y. et al. The extended McEvily model for fatigue crack growth analysis of Metal Structures. International Journal of Fatigue 2008, 30(11-12):1851-1860.

[7] Chen, F.L., Wang, F., Cui, W.C. An improved constitutive model to predict fatigue crack growth rate under variable amplitude loading with single and multiple overload. Journal of Engineering for the Maritime Environment 2011, 225(3):271-281.

[8] Cui, W.C., Wang, F., Huang, X.P. A Unified Fatigue Life Prediction (UFLP) method for marine structures. Marine Structures 2011, 24(2):153-181.

[9] Chen, F.L., Wang, F., Cui, W.C. Fatigue life prediction of engineering structures subjected to variable amplitude loading using the improved crack growth rate model. Fatigue & Fracture of Engineering Materials & Structures 2012, 35(3):278-290.

[10] Cui, W.C., Huang, X.P., Wang, F. Towards a unified fatigue life prediction method for marine structures. Zhejiang University Press and Springer. Zhejiang University Press, Hangzhou; Springer, Heidelberg, New York, Dordrecht, London. 2013.

[11] Wang, F., Cui, W.C. Approximate method to determine the model parameters in a new crack growth rate model [J]. Marine Structures 2009, 22:744-757.

[12] Cui, W.C., Wang, F. On determination of parameters of the unified fatigue crack growth rate model from tensile test data. 11th International Symposium on Practical Design of Ships and Other Floating Structures, Sept. 19-25, 2010, Rio de Janeiro, Brazil.

[13] Wang, F., Cui, W.C. On the engineering approach to estimating the parameters in an improved crack growth rate model for fatigue life prediction. Ships and Offshore Structures 2010, 5(3):227-241.

[14] Schütz, D., Lowak, H., De Jonge, J.B., Schijve, J. A standardised load sequence for flight simulation tests on transport aircraft wing structures. LBF-Report FB-106, NLR-Report TR 73.1973.

[15] Aicher, W., Branger, J., van Dijk, G.M., Ertelt, J., Hück, M., de Jonge, J.B., Lowak, H., Rhomberg, H., Schütz, D., Schütz, W. Description of a fighter aircraft loading standard for fatigue evaluation FALSTAFF. Common Report of FCW Emmen, LBF, NLR, IABG.1976.

[16] Li, S.S., Cui, W.C. Generation and application of a standardized load-time history to critical ship structural details. Ships and Offshore Structures 2014, 9(4):365-379.

[17] Berger, C., Eulitz, K.-G., Heuler, P., Kotte, K.-L., Naundorf, H., Schuetz, W., Sonsino, C.M., Wimmer, A., Zenner, H. Betriebsfestigkeit in Germany- an overview. International Journal of Fatigue 2002, 24:603-625.

[18] Gassner E. Jahrbuch 1941 der deutschen Luftfahrtforschung, I472.

[19] Gassner E. Luftwissen 1939; 6,61.

[20] Haibach, E., Fischer, R., Schütz, W., Hück, M. A standard random load sequence of Gaussian type recommended for general application in fatigue testing; its mathematical background and digital generation. In: Bathgate, R.G., editor. Fatigue Testing and Design. London: The Society of Environmental Engineers. 1976, 29.1-29.21.

[21] Edwards, P.R., Darts, J. Standardised fatigue loading sequences for helicopter rotors (HELIX and FELIX). RAE-Reports TR 84084 and TR 84085, Royal Aircraft Establishment. 1984.

[22] Breitkopf, G.E. Basic approach in the development of TURBISTAN, a loading standard for fighter aircraft engine disks. In: Potter, J.M., Watanabe, R.T., editors. Development of Fatigue Loading Spectra.ASTM-STP 1006. Philadelphia, PA: American Society for Testing and Materials. 1989, 65-78.

[23] Bergmann, J.W., Schütz, W. Standardisierter Lastablauf für heibe Turbinen- und Verdichterscheiben von Kampfflugzeugen-Hot TURBISTAN (Standardised load sequence for hot turbine and compressor discs of military aircraft). Report TF-2809, IABG Ottobrunn, Germany. 1990.

[24]Ten Have, A.A. WISPER and WISPERX-final definition of two standardised fatigue loading sequences for wind turbine blades. NLR Report CR 91476 L, Amsterdam. 1991.

[25] Lowak, H., de Jonge, J.B., Franz, T., Schütz, D. MiniTWIST—a shortened version of TWIST. NLR-Report MP 79018, LBF-Report TF-146. 1979.

[26] Heuler, P., Klätschke, H. Generation and use of standardised load spectra and load-time history. International Journal of Fatigue 2005, 27(8):974-990.

[27] Tucker, L.E., Bussa, S. The SAE cumulative fatigue damage test program. In: Wetzel, R.M., editor. Fatigue under Complex Loading-Analyses and Experiments. SAE AE-6 1977, 1-54.

[28] Schütz, D., Klätschke, H., Heuler, P. Standardized multiaxial load sequences for car wheel suspension components-car loading standard-CARLOS multi. Fraunhofer-Institut für Betriebsfestigkeit LBF),

Darmstadt. Report No. FB-201. 1994.

[29] Schütz, D., Klätschke, H. Standardized load sequences for car powertrains with manual gears-car loading standard-CARLOS PTM. Fraunhofer-Institut für Betriebsfestigkeit (LBF), Darmstadt. Report No. 7558. 1997.

[30] Klätschke, H. Standardized load sequences for car powertrains with automatic gears-car loading standard-CARLOS PTA. Fraunhofer-Institut für Betriebsfestigkeit (LBF), Darmstadt. Report No. 110310/110370. 2002.

[31] Sonsino, C.M., Klätschke, H., Schütz, W., Hück, M. Standardized load sequence for offshore structures-wave action standard history-WASH 1. Fraunhofer-Institut für Betriebsfestigkeit (LBF), Industrieanlagen-Betriebsgesellschaft mbH (IABG). LBF-Report No. FB-181, 1988; IABG-Report No. TF-2347, 1988.

[32] Schütz, W., Klätschke, H., Hück, M., Sonsino, C.M. Standardized load sequence for offshore structures-WASH I. Fatigue & Fracture of Engineering Materials & Structures 1990, 13(1):15-29.

[33] Tomita, Y., Matoba, M., Kawabe, H. Fatigue crack growth behavior under random loading model simulating real encountered wave condition. Marine Structures 1995, 8:407-422.

[34] Li, S.S., Cui, W.C. On generation of standardized load-time histories and standardized load spectra. Journal of Ship Mechanics 2011, 15(12):1405-1415.

[35] Li, S.S., Cui, W.C. Random load sequence effect on fatigue crack propagation of marine structure. Journal of Ship Mechanics 2014, 18(1-2):139-151. [In Chinese].

[36] DNV. Fatigue assessment of ship structures. Classification note 30.7. 2005.

[37] Schijve, J. The accumulation of fatigue damage in aircraft materials and structures. AGARD-AG-157. Advisory Group for Aerospace Research and Development. Neuilly-sur-Seine, France. 1972.

[38] Heuler, P., Seeger, T. Criterion for omission of variable amplitude loading histories. International Journal of Fatigue 1986, 8(4):225-30.

[39] Conle, F.A. An examination of variable amplitude histories in fatigue. PhD thesis. University of Waterloo, Canada. 1979.

[40] Johannesson, P. Extrapolation of load histories and spectra. Fatigue & Fracture of Engineering Materials & Structures 2006, 29:201-207.

[41] Li, S.S., Wang, Z.B., Cui, W.C. On implementing a practical algorithm to generate fatigue loading history or spectrum from short time measurement. Journal of Ship Mechanics 2011, 15:286-300.

[42] Rhee, H.C., Han, S., Gipson, G.S. Reliability of solution method and empirical formulas of stress intensity factors for weld toe cracks of tubular joints. Journal of Offshore Mechanics and Arctic Engineering 1991, 3:441-452.