2020

Guidance for Fatigue Strength Assessment Including Springing

GC-35-E

KR

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APPLICATION OF "Guidance for Fatigue Strength Assessment Including Springing"

Unless expressly specified otherwise, the requirements in the Guidance apply to ships for which contracts for construction are signed on or after 1 July 2020.

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CHAPTER 1 GENERAL

Section 1 General

101. Application

1. This guidance is for assessing the fatigue strength of the hull structure taking into account the vibration response of the ship in waves and can be assessed in addition to **Pt.3, Annex 3-3 Guidance for the Fatigue Strength Assessment of Ship Structures** of **Guidance relating to Rules for the Classification of Steel Ships** upon request by the applicant.
2. The springing is caused by the wave load and the resonance of the hull girder. The effect of springing is important for a ship with large slenderness ratio with low hull girder natural frequency or large vessels. Whipping is a vibration response that occurs when impact load such as slamming is applied to a ship, and its effect is important for ships with characteristics such as high speed and large flare that can cause large slamming loads. Whipping is often evaluated in view of ultimate load, but this guidance evaluates the effect of whipping in terms of fatigue strength evaluation.
3. Although this guidance cover vibration response analysis using computer simulation method and fatigue strength evaluation method by stress calculation, through a model test, the method of evaluating the fatigue strength of structural details by applying the stress concentration factor after measuring the vibration influence on the longitudinal bending moment and torsional moment can also be used.
4. When evaluating the fatigue strength considering vibration response in waves other than those provided in this guidance, sufficient data on the applied theory and verification of program should be provided and be approved by the Society.

102. Class Notations

"**SeaTrust(SPR1)**" or "**SeaTrust(SPR2)**" notation may be assigned upon request of the applicant(shipowner or shipbuilder), once review has been made in accordance with this guidance and is considered appropriate.

Section 2 Assessment Procedure

201. General

1. The fatigue strength assessment procedure considering springing can be divided into a linear springing assessment procedure and a nonlinear springing assessment procedure taking into account whipping as shown in **Fig. 1.1**.
2. The "**SeaTrust (SPR1)**" and "**SeaTrust (SPR2)**" notations are given for linear springing assessment procedure and nonlinear springing assessment procedure respectively.

202. Linear springing assessment

1. Based on the stress transfer function obtained from the results of linear hydro-elastic simulation, the effect of wave and hull resonance on the fatigue strength is evaluated in the frequency domain.
2. Due to the linear approximation in ship motion, nonlinear springing and whipping can not be taken into account, but the simulation time can be shortened by calculation in the frequency domain.

203. Nonlinear springing assessment

1. Effects of nonlinear springing and whipping on fatigue strength are considered and for this, the nonlinear hydro-elastic simulation in time domain is required.

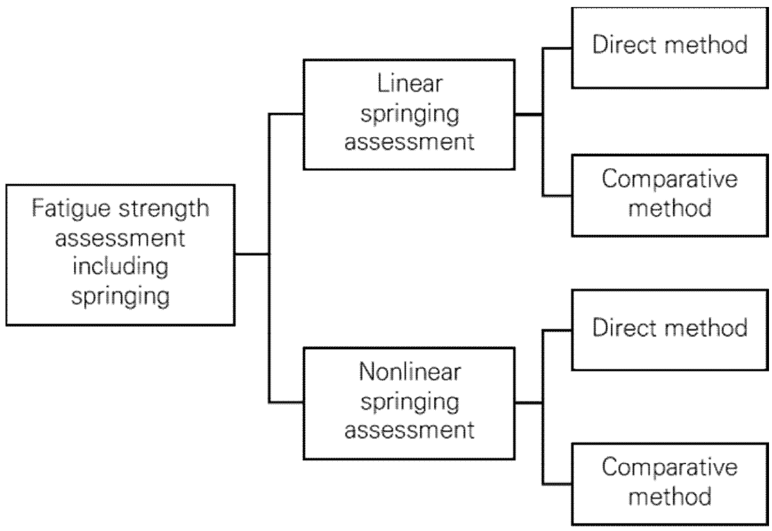

Fig. 1.1 Procedure for fatigue strength assessment including springing

2. Nonlinear hydro-elastic simulation can be performed relatively similar to actual seagoing conditions, but it takes a long analysis time, therefore it is necessary to reduce analysis time through selection of dominant sea states on fatigue strength.

204. Methods for calculating the fatigue damage

1. For the linear springing and nonlinear springing assessment, the direct method or comparative method is used, respectively.
2. The direct method is a method for calculating fatigue damage directly using stress results obtained from a hydro-elastic simulation. The procedure for analysis is similar to the linear spectral fatigue analysis method described in **Pt.3, Annex 3-3, 6.** of **Guidance relating to Rules for the Classification of Steel Ships**.
3. The comparative method is a method for calculating fatigue damage by multiplying the fatigue damage for the rigid body by the springing correlation coefficient which is obtained by comparing the simulation result including the influence of hydro-elasticity with the result which not.

Section 3 Assessment conditions

301. Loading conditions

1. For container ships, it is evaluated based on the loading condition which is expected to have the highest operation rate.
2. When the loading conditions are clearly separated by full load and ballast condition, such as bulk carriers, ore carriers and tankers, the operating ratio of these two loading conditions should be taken into account.
3. The ratio of periods during which the ship is not operated for loading, unloading and repair is excluded from the fatigue damage calculation.

302. Speed

1. The ship speed for fatigue assessment is to be taken as 2/3 of design speed.
2. When there is speed information of the ship in accordance with significant wave height, relevant information can be used.

303. Trading route and design fatigue life

The trading route and design fatigue life for evaluation follow the conditions in which the fatigue strength assessment were performed in accordance with the **Pt.3**, **Annex 3-3** of **Guidance relating to Rules for the Classification of Steel Ships**.

Section 4 Hydro-elastic simulation

401. General

1. The hydro-elastic simulation is to be carried out based on fluid-structure interaction.
2. The fluid domain assumes a three-dimensional potential flow and finds its solution by the boundary element method. Nonlinearity can be considered by using a weakly nonlinear approach that considers Froude-Krylov and hydrostatic forces (i.e. restoring forces) for the actual wetted area.

402. Simulation conditions

1. Wave incident angle

Simulation is performed at equal intervals of 30° or less taking into account all wave headings. In this case, if there is route information of the ship, the probability of occurrence of the predicted wave incidence can be considered. Otherwise, it is assumed that the probability of occurrence of the wave incidence is the same.

2. Wave frequency

In the linear springing assessment, the number of wave frequencies should be large enough so that the frequency characteristic of the stress transfer function can be adequately expressed and at least 40 wave frequencies should be considered in the range where the high frequency includes at least the primary longitudinal bending mode of the hull. In the nonlinear springing assessment, there should be more than 150 regular waves between the minimum frequency and the maximum frequency.

3. Simulation time interval

The simulation time interval is recommended to be 0.025 second or less.

4. Simulation time duration

The hydro-elastic simulation for nonlinear springing assessment is recommended to be performed for more than 3 hours for each short-term sea state.

5. Viscous roll damping

The viscous roll damping coefficient is recommended as a result of model testing or computational fluid dynamics, and a value of 5% can be used if there is no information.

403. Fluid model

1. The panels constituting the hull are to be of sufficient number of panels. In case of Rankine Source, more than 4,000 panels are recommended for semi-model as shown in **Fig. 1.2**, and the panel constituting the free surface of the fluid is appropriately created so that the radius of the free surface is more than three times the length of the ship.
2. The panel model for nonlinear analysis models up to the height of the strength deck of ship.

404. Calculation of slamming load

1. Slamming load calculation is performed in order to obtain the hull girder vibration responses caused by whipping.

2. The slamming load can be estimated by including the three-dimensional effect, or a calculation method from two-dimensional sections using GWM(Generalized Wagner Model) can be used. Where it is limited to calculate the slamming load for all wave headings, it may be applied for head and stern seas only.

405. Structural model for fatigue strength assessment

1. Structural model of ship

The three-dimensional structural model of the ship should be able to express the entire ship, and the size of the elements constituting the model should be less than the minimum girder or floor spacing. For secondary supporting members, beam elements with bending stiffness shall be used.

2. Model of fatigue strength assessment region

The finite element model of the structure is to consist of shell elements. At the hot spot region, the 4-noded quadrilateral shell elements of the size $t \times t$ are used, where t is the plate thickness. The weld bead is not included in the finite element model. In order to determine the surface stress distribution of the shell element, fictitious beams without stiffness are put on the connection line of shell element and stress evaluation is to be performed by the structural analysis. Also, stress evaluation is to be obtained from the shell element by the structural analysis. In case, FE models are to be based on as built scantlings and the beam element stresses are calculated taking account of shear flexibility.

3. Mass modeling

It is recommended that cargo masses such as containers be modeled using elements that do not affect the stiffness(e.g. Nastran RBE3 element), taking into account the possible center of gravity.

4. Structural damping

In case of container ships, a 2% value of the critical damping can be used.
For other vessels, relevant data should be submitted to the Society.

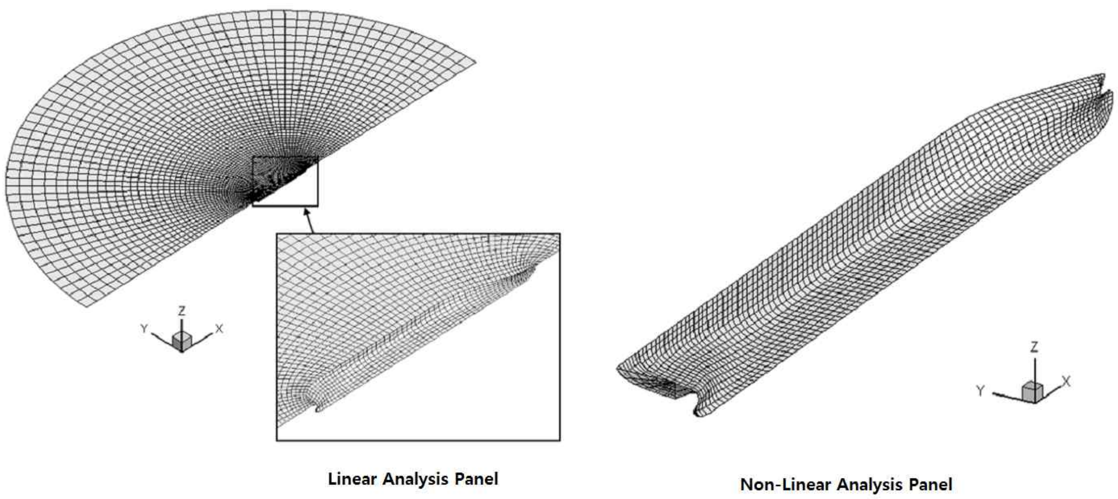

Fig. 1.2 Rankine panel model for simulation

406. Methods for calculating the stress

Since the hydro-elastic simulation, in the time domain, requires very large computational resource to accurately perform the structural analysis at every time interval for the global finite element model with considerable degrees of freedom, methods to reduce the computational resource required for structural analysis may be applied. This guidance adopts the modal superposition method and load conversion method, which are described follows.

1. Modal superposition method

(1) The modal superposition method calculates structural stress responses by superposition of stress components obtained by modal response of ship hull vibration.
(2) Eigenmodes to be used in hydro-elastic simulation are selected on the basis of the ship hull vibration analysis.
(3) The stress transformation matrix with respect to selected eigenmodes for elements which will be performed of fatigue strength assessment is to be obtained.
(4) The stress time series is calculated by combining the time series of modal responses which are calculated from hydro-elastic simulation and the stress transformation matrix which is obtained from (3).
(5) In general, where the number of eigenmodes which are used in modal superposition is high, the accuracy of structural response can be improved. However, since a higher-mode including local deformation can make influence to structural response, the eigenmodes for modal superposition method are to be carefully chosen after verification.

2. Load conversion method

(1) This method obtains ship hull vibration response by multiplying hull girder loads which are acting on cross section at ship longitudinal position obtained from hydro-elastic simulation to a stress transformation matrix of the global finite element model.
(2) The stress transformation matrix of finite element for which fatigue damage will be calculated is to be obtained by applying an unit hull girder load to the cross section where the finite element is.
(3) The magnitude of hull girder loads acting on cross section which is located in longitudinal position is to be calculated at every time interval in the time domain simulation. For cross sections at which hull girder loads are not calculated directly, the loads are to be estimated by interpolation.
(4) The stress of the target structural element is calculated by multiplying and superimposing the magnitude of each load component at the longitudinal position obtained in (3) to the stress transformation matrix for the unit load obtained in (2).
(5) The load conversion method is applicable conveniently to the hydro-elastic simulation of a simple structural model such as a beam model. However, since the accuracy of the application to an evaluation position where wave pressure or inertia force is dominant instead of hull girder loads may not be sufficient, particular attention is to be paid to application of the method.

3. Calculation of hot spot stress

The hot spot stress for the calculation of fatigue damage is to be estimated in accordance with **Pt.3, Annex 3-3, 2.** of **Guidance relating to Rules for the Classification of Steel Ships** using the analysis results obtained in **1.** or **2.** above. ⚓

CHAPTER 2 LINEAR SPRINGING ASSESSMENT

Section 1 Calculation of stress transfer function and response spectrum

101. Stress transfer function

1. The stress transfer function for wave heading, θ, and wave frequency, ω, is expressed as $H(\omega|\theta)$.
2. When the hydro-elastic simulation for the calculation of the stress transfer function is carried out in the time domain, the stress transfer function of the regular wave can be calculated by using the Fourier transform on the time series stress data obtained in the irregular wave condition.

102. Wave spectrum

The Modified Pierson-Moskowitz wave spectrum is recommended, which is defined in the following equation:

$$S_\eta(\omega|H_s,T_z) = \frac{H_s^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4\omega^{-5}\exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4\omega^{-4}\right]$$

ω = wave frequency, in $\mathrm{rad/s}$.

H_s = significant wave height, in m.

T_z = average Zero up-crossing wave period, in seconds.

103. Response spectrum

1. The response spectrum, $S(\omega|H_s,T_z,\theta)$, of the short-term sea state in the wave frequency domain can be estimated as follows using the wave spectrum and stress transfer function taking into account the thickness effect:

$$S(\omega|H_s,T_z,\theta) = (f_{thick}|H(\omega|\theta)|)^2 S_\eta(\omega|H_s,T_z)$$

f_{thick} = correction factor to consider the thickness effect is calculated as follows:

$$f_{thick} = \left(\frac{t}{22}\right)^n, \quad \text{(for } t > 22\text{)}$$

$$f_{thick} = 1, \quad \text{(for } t \le 22\text{)}$$

t = thickness of the member in way of the hot spot for welded joints or base material free edge, in mm.

n = thickness exponents according to the **Table 1** of **Pt 13, Ch 9, Sec 3** of **the Rules for the Classification of Steel Ships**.

2. The moments of the response spectrum taking into account the influence of short-crested waves in the encounter frequency domain are calculated as follows:

$$m_n = \int_\omega \sum_{\theta_0 - 90^\circ}^{\theta_0 + 90^\circ} f_s(\theta) \left| \omega - \frac{\omega^2 V}{g} cos\theta \right|^n S(\omega | H_s, T_z, \theta)$$

using a spreading function usually defined as $f_s(\theta) = kcos^2(\theta)$

where k is selected such that:

$$\sum_{\theta_0 - 90^\circ}^{\theta_0 + 90^\circ} f_s(\theta) = 1$$

where,
θ_0 = main wave heading.
θ = relative spreading around the main wave heading.

V = speed, in $\mathrm{m/s}$.
g = gravity acceleration, taken equal to 9.81 $\mathrm{m/s^2}$.

Section 2 Linear springing assessment by direct method

201. Procedure for linear springing assessment by direct method

1. Fig. 2.1 provides an illustration of the linear springing assessment procedure by direct method.
2. Using the response spectrum obtained from 103., the short-term fatigue damage is calculated in terms of the narrow-band approximation according to 202.
3. The short-term fatigue damage is obtained by multiplying a wide-band correction factor to the short-term fatigue damage obtained from 2. above.
4. The long-term fatigue damage obtained by accumulating the short-term fatigue damage obtained from 3. is defined as the fatigue damage including linear springing.

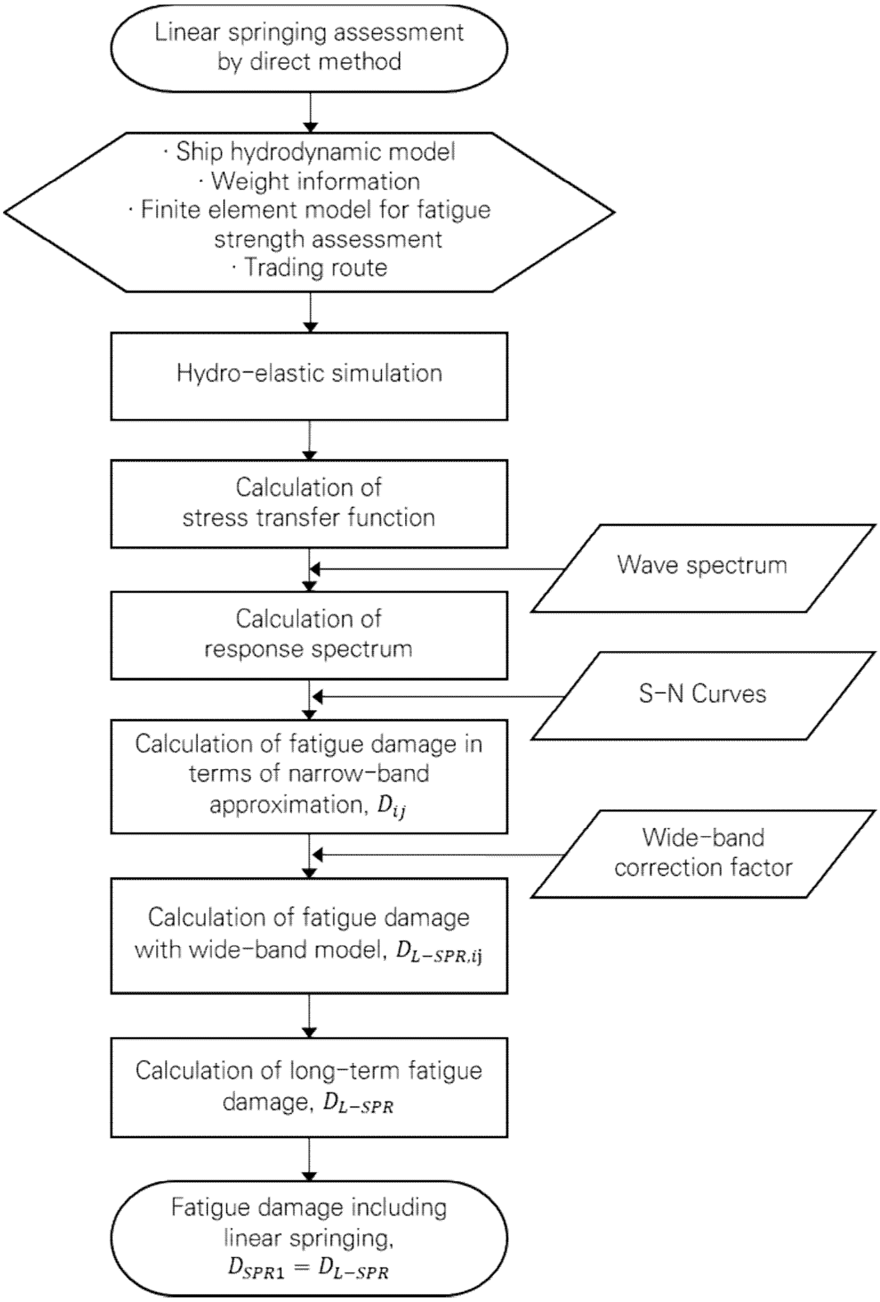

Fig. 2.1 Procedure for linear springing assessment by direct method

202. Short-term fatigue damage in terms of narrow-band approximation

The fatigue damage using the short-term closed-form method described in **Pt.3, Annex 3-3, 6.** of **Guidance relating to Rules for the Classification of Steel Ships** is as follows:

$$D_{ij} = 2^{\frac{3m}{2}} \frac{n_T}{K_2} \Gamma\left(\frac{m}{2}+1\right) \mu_{ij} r_{ij} p_{ij} m_{0ij}^{\frac{m}{2}}$$

Where (i,j) is the short-term sea state number defined by the significant wave, H_s, and the wave period, T_z, of the wave scatter diagram.

K_2, m = intercept and negative inverse slope of the S-N curve as specified in **Table 1** of **Pt.3, Annex 3-3** of **Guidance relating to Rules for the Classification of Steel Ships**, respectively.

n_T = total stress cycles for a life time of a ship given by the following formula:

$$n_T = f\,T$$

f = average frequency given by the following formula:

$$f = \sum_i \sum_j p_{ij} f_{ij}$$

p_{ij} = probability of occurrence of H_{si} and T_{zj}.
f_{ij} = zero up-crossing frequency of stress response in the sea state.

$$f_{ij} = \frac{1}{2\pi}\sqrt{\frac{m_{2ij}}{m_{0ij}}}$$

m_{nij} = moments of the response spectrum in the (i, j) short-term sea state, as specified in **103. 2.**

T = design fatigue life, in seconds.

$\Gamma(x)$ = complete Gamma function.
μ_{ij} = coefficient taking into account the change of inverse slope of the S-N curve is as follows:

$$\mu_{ij} = 1 - \frac{\gamma\left(\frac{m}{2}+1, t_{ij}\right) - \frac{1}{t_{ij}}\gamma\left(\frac{m+2}{2}+1, t_{ij}\right)}{\Gamma\left(\frac{m}{2}+1\right)}$$

$\gamma(a, x)$ = Incomplete Gamma function.

$$t_{ij} = \frac{s_7^2}{8m_{0ij}}$$

s_7 = the stress range of the design S-N curve at $N = 10^7$ cycles.

r_{ij} = ratio of the response zero up-crossing frequency in a given sea state to the average crossing frequency given by the following formula:

$$r_{ij} = \frac{f_{ij}}{f}$$

203. Short-term fatigue damage with wide-band model

1. In the hydro-elastic simulation including springing, the response in the high frequency region is included, and the stress response spectrum shows a wide-band distribution. To take this into account, this guidance applies the wide-band model proposed by Benasciutti-Tovo. Where a different wide-band model is required, relevant data is to be submitted for approval.

2. The fatigue damage, $D_{SPR1,ij}$, obtained by applying the wide-band correction factor, ρ_{ij}, to the fatigue damage, D_{ij}, obtained assuming the narrow-band response spectrum according to **201.** is as follows:

$$D_{L-SPR,ij} = \rho_{ij} D_{ij}$$

ρ_{ij} = wide-band correction factor for the (i, j) short-term sea state can be calculated as follows:

$$\rho_{ij} = b_{ij} + (1 - b_{ij})\, \alpha_{2ij}^{m-1}$$

α_{1ij}, α_{2ij} = bandwidth parameters of the stress response spectrum are as follows:

$$\alpha_{1ij} = \frac{m_{1ij}}{\sqrt{m_{0ij} m_{2ij}}}, \quad \alpha_{2ij} = \frac{m_{2ij}}{\sqrt{m_{0ij} m_{4ij}}} \qquad 0 \le \alpha_{1ij},\ \alpha_{2ij} \le 1$$

b_{ij} = weighting factor can be calculated as follows using the bandwidth parameters:

$$b_{ij} = \frac{(\alpha_{1ij} - \alpha_{2ij}) \left[1.112 (1 + \alpha_{1ij}\alpha_{2ij} - (\alpha_{1ij} + \alpha_{2ij})) e^{2.11\alpha_{2ij}} + (\alpha_{1ij} - \alpha_{2ij}) \right]}{(\alpha_{2ij} - 1)^2}$$

204. Long-term fatigue damage with wide-band model

1. Taking account of all heading directions and loading conditions, the long-term cumulative fatigue damage ratio in air is calculated as follows:

$$D_{L-SPR,air} = 2^{\frac{3m}{2}} \frac{n_T}{K_2} \Gamma\left(\frac{m}{2} + 1\right) \sum_i \sum_j \sum_k \sum_l \rho_{ijkl} \mu_{ijkl} r_{ijkl} p_{ijkl} m_{0ijkl}^{\frac{m}{2}}$$

K_2, m = intercept and negative inverse slope of the S-N curve as specified in **Table 1 (a)** of **Pt.3, Annex 3-3** of **Guidance relating to Rules for the Classification of Steel Ships**, respectively.

p_{ijkl} = combined probability given by the following formula:

$$p_{ijkl} = p_{ij} p_k p_l$$

p_k, p_l = probability for the heading angle and the loading condition, respectively.

2. For unprotected joints exposed to sea water, the fatigue damage ratio, $D_{SPR1,cor}$, is given by:

$$D_{L-SPR,cor} = 2^{\frac{3m}{2}} \frac{n_T}{K_2} \Gamma\left(\frac{m}{2}+1\right) \sum_i \sum_j \sum_k \sum_l \rho_{ijkl} r_{ijkl} p_{ijkl} m_{0ijkl}^{\frac{m}{2}}$$

K_2, m = intercept and negative inverse slope of the S-N curve as specified in **Table 1 (b)** of **Pt.3, Annex 3-3** of **Guidance relating to Rules for the Classification of Steel Ships**, respectively.

For the structural members protected by effective means in ballast tanks, the fatigue damage ratio, D_{L-SPR}, is to be calculated as follows:

$$D_{L-SPR} = 0.5 D_{L-SPR,air} + 0.5 D_{L-SPR,cor}$$

Cumulative fatigue damage, D_{L-SPR}, is defined as the fatigue damage including linear springing, D_{SPR1}.

3. The fatigue life , $T_{F,SPR1}$, considering linear springing for the members subject to fatigue strength assessment is calculated according to the following formula:

$$T_{F,SPR1} = \frac{T_D}{D_{SPR1}}$$

T_D = design fatigue life, in years.

Section 3 Linear springing assessment by comparative method

301. Procedure for linear springing assessment by comparative method

1. Fig. 2.2 provides an illustration of the linear springing assessment procedure by comparative method.
2. Long-term fatigue damage, D_{L-SPR}, with wide-band model is to be obtained from **204**.
3. The long-term fatigue damage, D_{L-RGD}, for rigid body is to be calculated using the stress transfer function in which hydro-elastic effect is excluded as illustrated in Fig. 2.2.
4. The linear springing coefficient, f_{SPR1}, is to be defined as a ratio of D_{L-SPR} and D_{L-RGD} which are long-term fatigue damage obtained from **2**. and **3**. above.
5. The fatigue damage, D_{SPR1}, including linear springing is to be obtained by multiplying a fatigue damage, D, calculated in accordance with **Pt.3, Annex 3-3, 6. (5)** of **Guidance relating to Rules for the Classification of Steel Ships** by the linear springing coefficient, f_{SPR1}.

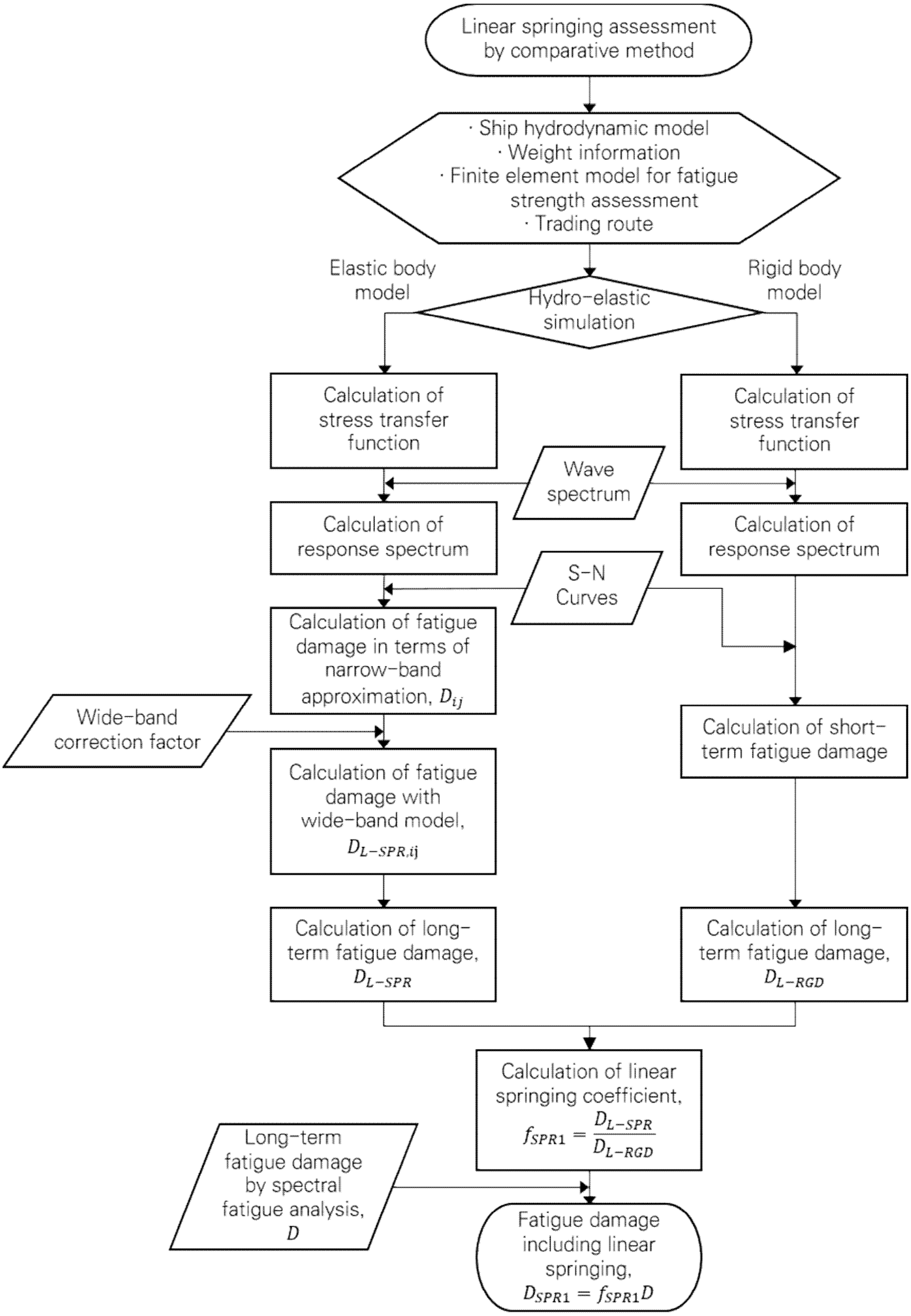

Fig. 2.2 Procedure for linear springing assessment by comparative method

302. Long-term fatigue damage excluding hydro-elastic effect

1. Long-term fatigue damage excluding hydro-elastic effect is calculated in accordance with **Pt.3, Annex 3-3, 6.** of **Guidance relating to Rules for the Classification of Steel Ships**. The stress transfer function used in the calculation of fatigue damage is obtained by simulation with a rigid body model, and the calculation of the stress transfer function is in accordance with **101**.
2. Instead of performing a separate simulation with the rigid body to calculate the stress transfer function excluding the elastic effect as **1.** above, it may be obtained by removing the high frequency range from the stress transfer function calculated according to **101**. The range which is to be removed from the original stress transfer function is an area over 90% of the first natural frequency for ship hull.
3. The fatigue damage, D_{L-RGD}, for the rigid body is defined as long-term fatigue damage obtained from 1. or 2. above.

303. Calculation of the linear springing coefficient and long-term fatigue damage

1. Linear springing coefficient, f_{SPR1}, is defined as follows:

$$f_{SPR1} = \frac{D_{L-SPR}}{D_{L-RGD}}$$

2. The long-term fatigue damage, D_{SPR1}, including linear springing by comparative method is derived as follows:

$$D_{SPR1} = f_{SPR1} D$$

D = damage by spectral fatigue analysis, see **Pt.3, Annex 3-3, 6. (5) (B)** of **Guidance relating to Rules for the Classification of Steel Ships**.

3. The fatigue life , $T_{F,SPR1}$, considering linear springing for the members subject to fatigue strength assessment is calculated according to the following formula:

$$T_{F,SPR1} = \frac{T_D}{D_{SPR1}}$$

T_D = design fatigue life, in years. ⫝̸

CHAPTER 3 NONLINEAR SPRINGING ASSESSMENT

Section 1 Nonlinear springing assessment by direct method

101. Procedure for nonlinear springing assessment by direct method

1. Fig. 3.1 provides an illustration of the nonlinear springing assessment procedure by direct method.
2. Dominant sea states for fatigue damage evaluated in accordance with **Pt.3, Annex 3-3, 6.** of **Guidance relating to Rules for the Classification of Steel Ships** is to be selected.
3. Stress time series are to be obtained from nonlinear hydro-elastic simulation including slamming in dominant sea states which are selected in 2. above.
4. Short-term fatigue damage is to be evaluated by applying a linear cumulative damage summation(Palmgren-Miner's rule) and S-N curves to the stress range distribution, which is calculated by applying the rainflow-counting method to the stress time series obtained from **2**.
5. The fatigue damage including nonlinear springing is to be obtained by applying correction factors for entire sea states and short-crested wave effect to the fatigue damage calculated from 4. above.

102. Selection of dominant sea states for the fatigue damage

1. Simulation in the time domain is required to evaluate the effect of springing and slamming due to nonlinearity of ship motion on fatigue strength.
2. Because of the long process time required for nonlinear simulation in the time domain, it is difficult to simulate all short-term sea states directly. This guidance adopts a method for evaluating fatigue damage including nonlinear springing from the results of short-term sea states which contribute large influence on fatigue damage in **Pt.3, Annex 3-3, 6.** of **Guidance relating to Rules for the Classification of Steel Ships**.
3. The spectral fatigue damage for short-term sea state is defined by D_{ijkl} taking into consideration ship-to-wave heading, k, and loading condition, l, in addition to the fatigue damage, D_{ij}, which is defined in **Pt.3, Annex 3-3, 6. (4) (B)** of **Guidance relating to Rules for the Classification of Steel Ships**. The fatigue damage contribution, d_{ijkl}, for each short-term sea state is to be calculated by dividing the calculated short-term sea state fatigue damage, D_{ijkl}, by the long-term fatigue damage, D_l, under a given loading condition.

$$d_{ijkl} = \frac{D_{ijkl}}{D_l}$$

4. The number of short-term sea states for which the cumulated fatigue damage exceeds the cumulative contribution, C_d, is to be calculated. The value of cumulative contribution value is to be determined in consultation with the Society, and a value of 0.5 or higher is recommended. For efficient calculation, the number of short-term sea states, n, may be obtained by sorting from the short-term sea state with a large contribution to fatigue damage as shown in the following equation. These n short-term sea states are defined as the dominant sea states.

n = number of sea states is to be obtained as follows:

$$\sum_{r=1}^{n} d_r > C_d$$

d_r = fatigue damage contribution of the r-th short-term sea state when sorting from short-term sea state with high fatigue damage contribution.

C_d = the cumulative contribution.

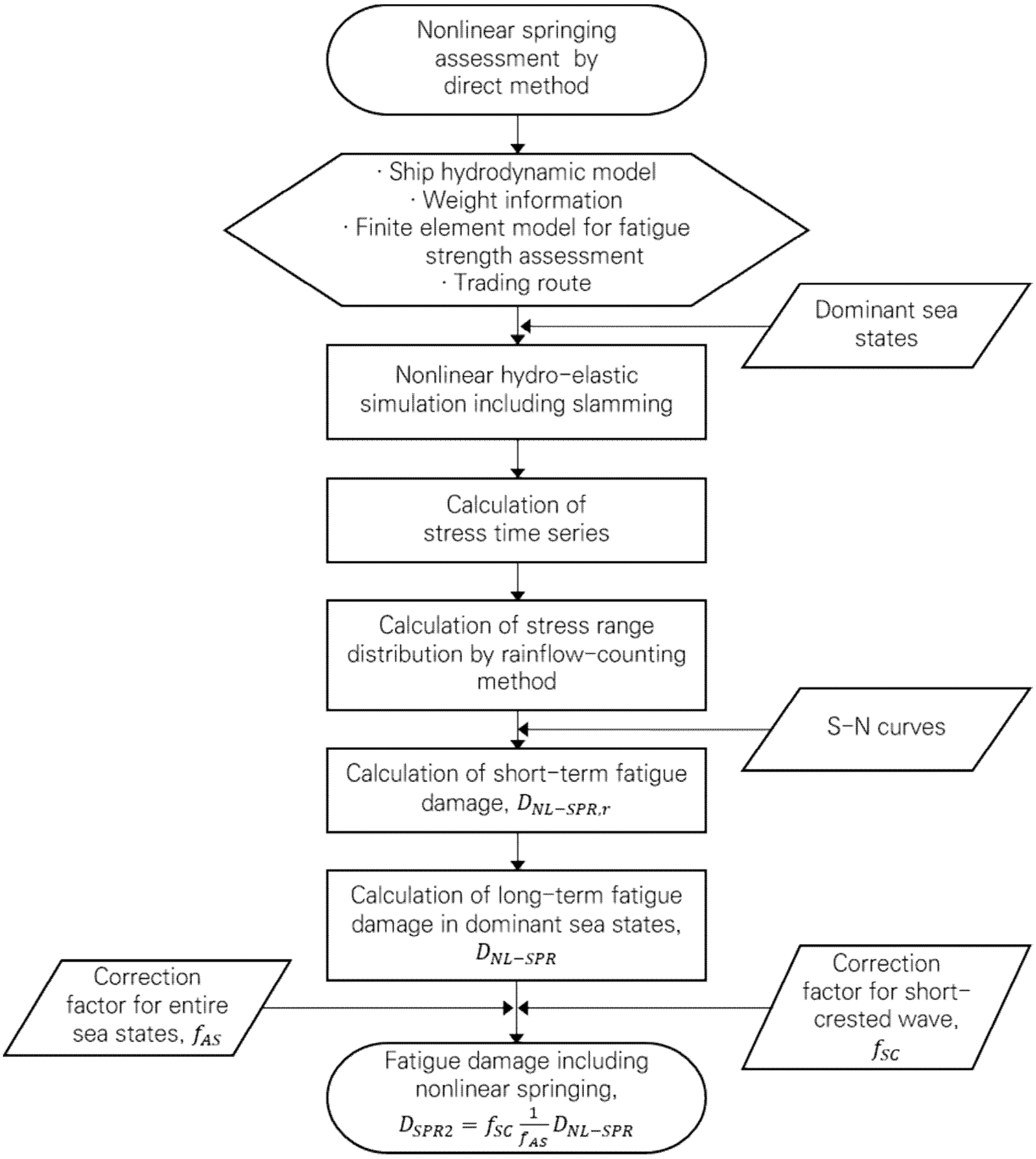

Fig. 3.1 Procedure for nonlinear springing assessment by direct method

103. Calculation of fatigue damage by the rainflow-counting method

1. The number of cycles of the reference stress range can be obtained using the rainflow-counting method to the stress time series of short-term sea states including vibration response due to springing and whipping.

2. Short-term fatigue damage, $D_{NL-SPR,r}$, is calculated by applying the following Palmgren-Miner's linear cumulative damage law and the probability of occurrence of each short-term sea state to the reference stress range and its number of cycles.

$$D_{NL-SPR,r} = p_r \frac{T}{T_r} \sum \frac{n_i}{N_i}$$

p_r = probability of occurrence of r-th short-term sea state.

T = design fatigue life of the ship as defined in **Ch. 2, 202.** of this guidance.

T_r = simulation time of r-th short-term sea state, in seconds.

$n_{\Delta\sigma i}$ = estimated number of cycles at the reference stress range by the rainflow-counting method.

$N_{\Delta\sigma i}$ = number of constant amplitude load cycles to failure according to the design S-N curve at the reference stress range.

3. Cumulative fatigue damage, D_{NL-SPR}, in the dominant sea states is derived by summation of short-term fatigue damage as follows:

$$D_{NL-SPR} = \sum_{r=1}^{n} D_{NL-SPR,r}$$

n = number of the dominant sea states defined in 102. 4.

104. Correction factor for entire sea states

A correction factor, f_{AS}, to take into consideration entire sea states is defined as following expression, which is a ratio of fatigue damage in the dominant sea states and entire sea states from spectral fatigue analysis results.

$$f_{AS} = \frac{\sum_{r=1}^{n} D_{l,r}}{D_l}$$

$D_{l,r}$ = spectral fatigue damage in r-th dominant sea state under the loading condition l.

D_l = cumulative spectral fatigue damage in entire sea states under the loading condition l.

105. Correction factor for effect of short-crested wave

When the hydro-elastic simulation for nonlinear springing and whipping is carried out under long-crested wave condition, a correction factor can be used to consider the effect of short-crested wave. In this case, the correction factor, f_{SC}, can be estimated from the results of spectral fatigue analysis as the following expression.

$$f_{SC} = \frac{D_l}{D_{l-LC}}$$

The fatigue damage, D_{l-LC}, under long-crested wave condition is to be calculated with spectral moments which is obtained by excluding terms of spreading function from the moments defined in **Pt.3, Annex 3-3, 6. (3) (C)** of **Guidance relating to Rules for the Classification of Steel Ships** as follows:

$$m_{0-LC} = \int_{\omega} S(\omega|H_s, T_z, \theta)$$

$$m_{2-LC} = \int_{\omega} \left| \omega - \frac{\omega^2 V}{g} cos\theta \right|^2 S(\omega|H_s, T_z, \theta)$$

106. Calculation of fatigue damage including nonlinear springing

1. Fatigue damage, D_{SPR2}, including nonlinear springing is derived by applying correction factors obtained from 104. and 105 to fatigue damage which is calculated in dominant sea states according to 103 as the following expression.:

$$D_{SPR2} = f_{SC} \frac{1}{f_{AS}} D_{NL-SPR}$$

2. Fatigue life, $T_{F,SPR2}$, including nonlinear springing is obtained as follows:

$$T_{F,SPR2} = \frac{T_D}{D_{SPR2}}$$

Section 2 Nonlinear springing assessment by comparative method

201. Procedure for nonlinear springing assessment by comparative method

1. Fig. 3.2 provides an illustration of the nonlinear springing assessment procedure by comparative method.
2. Dominant sea states for fatigue damage which is evaluated in accordance with **Pt.3, Annex 3-3, 6.** of **Guidance relating to Rules for the Classification of Steel Ships** is to be selected.
3. Time series of stress are to be obtained from nonlinear hydro-elastic simulation including slamming in dominant sea states which are selected in 2. above.
4. Short-term fatigue damage is to be evaluated by applying a linear cumulative damage summation(Palmgren-Miner's rule) and S-N curves to the stress range distribution, which is calculated by applying the rainflow-counting method to the stress time series obtained from **2**.
5. The fatigue damage, D_{NL-SPR}, including nonlinear springing is to be obtained by applying correction factors for entire sea states and short-crested wave effect to the fatigue damage calculated from **4.** above.
6. The fatigue damage, D_{NL-RGD}, for rigid body is to be obtained by applying 4. and 5. with time series not including hydro-elasticity.

7. The nonlinear springing coefficient, f_{SPR2}, is to be defined as a ratio of D_{NL-SPR} and D_{NL-RGD} which are long-term fatigue damage obtained from 5. and 6.

8. The fatigue damage, D_{SPR2}, including nonlinear springing is to be obtained by multiplying a fatigue damage, D, calculated in accordance with **Pt.3, Annex 3-3, 6. (5)** of **Guidance relating to Rules for the Classification of Steel Ships** by the nonlinear springing coefficient, f_{SPR2}.

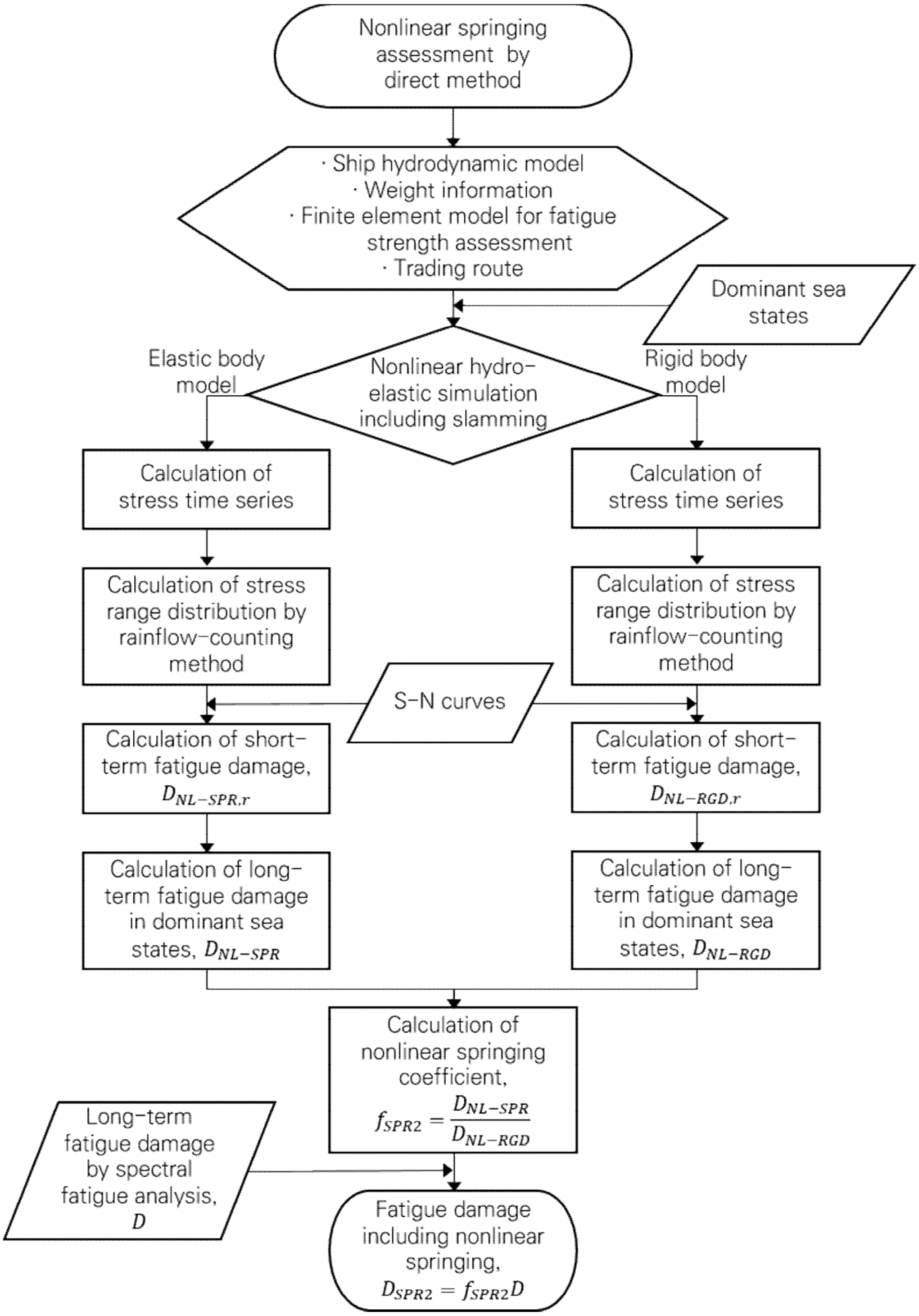

Fig. 3.2 Procedure for nonlinear springing assessment by comparative method

202. Long-term fatigue damage excluding hydro-elastic effect

1. Time series of stress are to be obtained from simulation for the rigid body in dominant sea states which are defined in 102. The time series of wave elevation used in the simulation should be the same as the time series used in hydro-elastic simulation including nonlinear springing at this stage.
2. Instead of performing a separate simulation with the rigid body to calculate the time series of stress excluding the elastic effect as 1. above, it may be obtained by applying low-pass filter to the time series calculated from hydro-elastic simulation.
3. The fatigue damage, D_{NL-RGD}, excluding hydro-elastic effect is defined as the damage evaluated using the time series of stress obtained from 1. or 2. above.

203. Calculation of the nonlinear springing coefficient and long-term fatigue damage

1. The nonlinear springing coefficient, f_{SPR2}, is defined as follows:

$$f_{SPR2} = \frac{D_{NL-SPR}}{D_{NL-RGD}}$$

2. The fatigue damage, D_{SPR2}, including nonlinear springing by comparative method is derived as follows:

$$D_{SPR2} = f_{SPR2} D$$

where:

D = long-term fatigue damage by spectral fatigue analysis, see **Pt.3, Annex 3-3, 6. (5) (B)** of **Guidance relating to Rules for the Classification of Steel Ships**

3. Fatigue life, $T_{F,SPR2}$, including nonlinear springing is obtained as follows:

$$T_{F,SPR2} = \frac{T_D}{D_{SPR2}}$$

where:

T_D = fatigue life, in years

Section 3 Nonlinear springing assessment for low-speed blunt ships where vertical bending moment is significant

301. Application

1. Nonlinear springing assessment may be performed in head seas conditions for ships where stress ranges by vertical bending moment are significant to fatigue damage, e.g. very large ore carrier, to simplify the assessment, then the comparative method described in Sec. 2 is to be applied for the assessment.
2. Since low-speed blunt ships have comparatively high stiffness, natural frequencies of ship hull are high and a vertical mode is the lowest eigenmode in general. Where natural frequencies are high, the effect on fatigue damage by linear springing is comparatively low, and it is essential that due consideration is given to the ship hull vibration response including whipping.

302. Selection of dominant sea states for the fatigue damage

1. The procedure described in **102.** is to be applied for selection of dominant sea states, but ship-to-wave headings are confined only to head seas condition.

2. The fatigue damage contribution, d_{180ijl}, under head seas condition is to be obtained as follows:

$$d_{180ijl} = \frac{D_{180ijl}}{D_{180l}}$$

where:

D_{180ijl} = fatigue damage in a short-term sea state under head seas condition

D_{180l} = long-term fatigue damage under head seas condition

3. Dominant sea states are selected according to **102. 4.**

303. Calculation of concentrated stress and fatigue damage

1. Where the effect of vertical bending moment on fatigue damage is significant, the concentrated stress for fatigue strength assessment may be obtained from simplified stress analysis which is using nominal stresses and stress concentration factors instead of the procedure according to **Sec. 1 406**.

2. Time series of hull girder loads may be calculated with global 1-D finite element model consists of beam elements which properly represent for stiffness and weight distribution of a ship. Time series of stress for the fatigue strength assessment is to be obtained by multiplying the time series of nominal stress by stress concentration factors in accordance with **Pt.3, Annex 3-3, 4. (2)** and **(3)** of **Guidance relating to Rules for the Classification of Steel Ships**.

3. Instead of performing a separate simulation with the rigid body to calculate the time series of stress excluding the elastic effect, it may be obtained by applying low-pass filter to the time series obtained from **2.** above.

4. The fatigue damage D_{NL-SPR} and D_{NL-RGD}, with and without the springing effect on fatigue damage, are to be obtained from by applying the rainflow-counting method described in 103. to the time series of stress obtained from 2. and 3. above.

304. Calculation of the nonlinear springing coefficient and long-term fatigue damage

1. The nonlinear springing coefficient, f_{SPR2}, is defined as follows:

$$f_{SPR2} = \frac{D_{NL-SPR}}{D_{NL-RGD}}$$

2. The fatigue damage, D_{SPR2}, including nonlinear springing by comparative method is derived as follows:

$$D_{SPR2} = f_{SPR2} D_{RGD}$$

where:

D_{RGD} = long-term fatigue damage according to **Pt.3, Annex 3-3** of **Guidance relating to Rules for the Classification of Steel Ships**

3. Fatigue life, $T_{F,SPR2}$, including nonlinear springing is obtained as follows:

$$T_{F,SPR2} = \frac{T_D}{D_{SPR2}}$$

where:

T_D = fatigue life, in years. ⚓

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