Technical report

Soundness Evaluation Method Using S-N Curve for Equipment Supports Subjected to Machine Vibrations

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Abstract

The degradation factors considered in the evaluation of long-term soundness of reinforced concrete structures in nuclear facilities in Japan are heat (high temperature), irradiation, carbonation, chloride penetration, alkali silica reaction, and machine vibration. As described in the “Guidelines for Maintenance and Management of Structures in Nuclear Facilities,” the soundness evaluation of equipment supports against machine vibration is very rudimentary compared with the evaluation methods against other factors since the degradation state due to machine vibration cannot be identified until cracks are visually detected as degradation phenomena. The phenomenon of fatigue of equipment supports can be expressed using an S-N curve that shows the relation between the maximum stress ratio and the fatigue life under repeated loading. During normal operation of nuclear facilities, the maximum stress ratio of repeated load is very low and less than the long-term allowable stress level, and the fatigue life is very long. Since the number of load repetition can be known from the operation period of the facility, soundness against fatigue can be evaluated using an S-N curve. In this paper, a soundness evaluation method using an S-N curve for equipment supports subjected to machine vibrations is proposed.

1. Background

Long-term operation of nuclear power plants is a common issue for the countries that own them, and for that purpose it is essential to understand the soundness of the structures, systems, and components. In particular, since concrete structures in nuclear facilities are almost irreplaceable, their soundness evaluation becomes increasingly important as the operation period of the facilities grows longer. For this reason, the Architectural Institute of Japan published “Guidelines for Maintenance and Management of Structures in Nuclear Facilities” in 2008 (AIJ 2008) and revised these Guidelines in 2015 (AIJ 2015). In addition, in order to introduce the Guidelines overseas, the English version of the Guidelines will be released in 2021 (AIJ 2021).

The maintenance prescribed in the Guidelines can be divided into two categories: maintenance for checking current soundness and maintenance for evaluating long-term soundness. For checking current soundness of concrete structures in nuclear facilities, visual and non-destructive testing will be used to assess the degree of degradation phenomena. For maintaining soundness into the future, it is necessary to evaluate soundness based on degradation factors and mechanisms that cause

degradation phenomena.

The degradation factors considered in the evaluation of long-term soundness of structures are heat (high temperature), irradiation, carbonation, chloride penetration, alkali silica reaction (ASR), and machine vibration. The ways of evaluating the soundness of structures are summarized in **Table 1**.

For heat and irradiation, threshold values are set for the soundness of structures. As long as the temperature or the fluence/dosage evaluated by analyses or measurement in the future are less than the threshold values, the structures are regarded as sound going into the future.

For carbonation and chloride penetration, the degradation mechanisms leading to the reinforcement corrosion are well understood, and we can evaluate the degree of degradation by measuring chloride content or carbonation depth using concrete samples.

Although the degradation mechanisms for ASR leading to concrete swelling and cracking are well understood, it is quite difficult to detect signs of degradation unless the degree of degradation is serious. The risk of ASR can be checked from records of the testing of aggregate alkali silica reactivity by a method such as the chemical method, mortar-bar method, or concrete bar method. Even after the detection of cracking and so on, it is possible to maintain the long-term soundness of a concrete structure by monitoring the progress of degradation phenomena because the progress rate of ASR is quite slow.

For machine vibration, the degradation state cannot be identified until cracks are visually detected as degradation phenomena, which is hardly ideal for the practical evaluation of long-term soundness. Therefore, we decided to carry out the present research on a soundness evaluation method for equipment supports, in cooperation with electric power companies.

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Table 1 Degradation factors and evaluation methods.

Degradation factor	Evaluation index	Evaluation criterion
Heat	Concrete temperature	Within 65°C for general parts Within 90°C for local parts (piping penetration, etc.)
Heat * (shielding performance)	Highest internal temperature	Within 88°C for the heat due to neutrons Within 177°C for the heat due to gamma rays
	Ambient temperature	Within 71°C when the heat is due to neutrons Within 149°C when the heat is due to gamma rays
Radiation exposure	Radiation exposure	1×10^{20} n/cm ² or less for neutron fluence 2×10^8 Gy (2×10^{10} rad) or less for gamma ray dose
Carbonation	Carbonation depth	During the in-service period, the carbonation depth has not increased so much as to cause rebar corrosion.
Chloride penetration	Corrosion amount	The rebar corrosion amount has/hasn't reached the level for cracking to occur.
	Amount of chloride ions	The amount of chloride ions at rebars has/hasn't reached the level for rebar corrosion to occur.
Alkali silica reaction	Cracking	Cracks due to ASR have/haven't been detected.
	Alkali silica reactivity of aggregate	Records of the aggregate reactivity tests such as chemical method, mortar-bar method, and concrete bar method, have been reviewed.
Machine vibration	Cracking	Cracks due to machine vibration have/haven't been detected.

*: The temperature is checked for the shielding performance of the concrete structures and other factors are checked for structural safety.

2. Design of anchor specimens

2.1 Tension loads

According to “Design Recommendations for Various Composite Constructions,” (AIJ 2010), the tensile force of a stud anchor due to concrete cone failure can be obtained by Equation (1), in which the angle of the cone is assumed to be 45°. The effects of the edge and spacing between anchors can be taken into account in evaluating the effective projected area of the cone failure surface.

$$p_{ta} = k \cdot 0.31\sqrt{F_c} \cdot A_c \quad (1)$$

where p_{ta} : Allowable tensile force per anchor bolt determined by concrete cone failure (p_{ta} is regarded as the tensile strength in this paper.).

F_c : Design strength of concrete (N/mm²).

$0.31\sqrt{F_c}$: Tensile strength of concrete for concrete cone

failure.

$A_c = \pi \cdot l_e(l_e + D)$: Horizontal projected area of cone failure surface (Fig. 1(a)). The horizontal projected area when multiple anchor bolts are installed in close proximity is determined according to Fig. 1(b). When anchor bolt(s) are close to the edge, the missing area is considered in calculating the horizontal projected area.

l_e : Effective embedment depth of anchor bolts in concrete.

d, D : Diameter of anchor bolt and anchor head.

k : Reduction factor for long-term and short-term allowable tensile load, For long-term allowable tensile load, $k = 1/3$ according to AIJ (2010), and 0.3 according to JEAG (1991).

2.2 Shear loads

According to the Guidelines (AIJ 2010), the shear force of the stud anchor due to concrete failure can be obtained

Fig. 1 Horizontal projected area of cone failure surface (AIJ 2010).

by the smaller of the values calculated by Equations (2) and (3). The effective embedment depth l_e in Fig. 1 is evaluated longer by Equation (4) so that the tensile strength of the anchor is determined by the yield strength of the anchor bolt and that the concrete failure will not occur. The required effective embedment depth tends to be longer with decreasing distance from the center of the anchor bolt to the edge.

$$p_{sa1} = k \cdot 0.5 \sqrt{F_c \cdot E_c} \cdot a_s \quad (2)$$

$$p_{sa2} = k \cdot 0.31 \sqrt{F_c} \cdot A_{qc} \quad (3)$$

$$\sigma_s \cdot a_s \leq 0.31 \sqrt{F_c} \cdot A_c \quad (4)$$

where p_{sa} : Allowable shear force per anchor bolt due to concrete failure, the smaller of the forces obtained by Equation (2) for bearing failure of concrete by stud or Equation (3) for shear cone failure (p_{sa} is regarded as the shear strength in this paper.).

F_c : Design strength of concrete (N/mm²).

E_c : Young's modulus of concrete (N/mm²).

$0.5 \sqrt{F_c \cdot E_c}$: Bearing strength of concrete.

$0.31 \sqrt{F_c}$: Tensile strength of concrete for concrete cone failure.

a_s : Axial cross-sectional area of stud anchor.

$A_{qc} = 0.5 \cdot \pi \cdot c^2$: Vertical projected area of cone failure surface on the side surface in the direction of shear force (Fig. 2).

c : Distance from the center of the anchor bolt to the edge.

σ_s, σ_y : Shear strength and yield strength of anchor bolt, and $\sigma_s = 0.7 \cdot \sigma_y$.

a_s : Sectional area of anchor bolt.

k : Reduction factor for long-term and short-term allowable tensile load, For long-term allowable tensile load, $k = 1/3$ according to AIJ (2010), 0.3 for Equation (2), and 0.4 for Equation (3), according to JEAG (1991).

$A_c = \pi \cdot l_e (l_e + D)$: Horizontal projected area of cone failure surface (Fig. 1(a)).

l_e : Effective embedment depth of anchor bolts in concrete.

Fig. 2 Vertical projected area of the side (AIJ 2010).

2.3 Combination of tension loads and shear loads

According to the Guidelines (AIJ 2010), the combined force should be examined when tensile force p and shear force q act at the same time. The combined force per anchor bolt can be checked by Equation (5).

$$\left\{ \frac{p}{p_{ta}} \right\}^2 + \left\{ \frac{q}{p_{sa}} \right\}^2 \leq 1 \quad (5)$$

where p_{ta} , p_{sa} : Allowable tension force and shear force.

3. Residual strength test after cyclic loading

A summary of Kontani *et al.* (2016) is provided in this section for reference.

3.1 Concrete cylinder specimens

The authors performed residual strength tests after cyclic loading using plain concrete cylinder specimens 100 mm in diameter and 200 mm long to investigate whether or not cyclic loading reduces the strength and the rigidity of concrete in compression. The water-to-cement ratio was 59% and the compressive strength was 37.3 MPa during the tests. The 37 specimens survived 316 to two million load cycles with speed of 5 Hz at the maximum stress ratios of 0.75, 0.65, 0.33 and the minimum ratio of 0.05 of the static strength without cyclic loading.

The residual strength after cyclic loading were 1% to 9% higher than the static strength without cyclic loading.

Figure 3 shows the relationship between compressive load and strain of two specimens. The curves of only representative cycles are shown for the cyclic loadings. Regarding deformation, the cylindrical specimen after two million load cycles with the maximum stress ratio 0.33 exhibited residual strain of around 250 micros, as can be seen in Fig. 3(b).

3.2 Anchor specimens

The authors also performed residual strength tests on the anchor specimens after cyclic loading to investigate the effects of cyclic loading on the strength and the rigidity of the anchor specimens. The details of the headed stud anchors and specimens are shown in Fig. 4. No reinforcement was placed in the area where cone failure was

expected. The water-to-cement ratio was 60% and the compressive strength was 32-33 MPa at the tests. The maximum stress ratios of cyclic loading were set at 0.75, 0.65, and 0.22. The process of cyclic loading and the residual strength ratio after cyclic loading against the static test of the specimen are summarized in Fig. 5. The cyclic loading process is expressed by the arrow in the X-direction and the residual anchor strength are shown by the arrow in the Y-direction. All the residual anchor strengths are equal to or greater (by up to 17%) than the static strength of the specimen without cyclic loading. Increasing the number of load cycles increases the residual strength of the anchor specimen after cyclic loading.

Figures 6 and 7 show the test results of the anchor

specimen with 10 million load cycles at the maximum stress ratio of 0.22. Figure 6 shows the relationships between the tensile loads and pullout displacement of the anchor during fatigue loading as well as static loading with the results of the static test without cyclic loading. Figure 7 shows the relationship between pullout displacement of the anchor and the number of load cycles at the maximum and minimum stress ratios. In this case, no inelastic displacement was observed even after 10 million load cycles.

3.3 Effect of cyclic loading on strength and stiffness

The residual strength after cyclic loading was 1% to 9% higher than the static strength without cyclic loading for

Fig. 3 Compressive load vs. strain from Kontani *et al.* (2016).

Fig. 4 Stud anchor specimen from Kontani *et al.* (2016).

Fig. 5 Test results compared with S-N curves from Kontani *et al.* (2016).

Fig. 6 Tensile loads vs. pullout displacement of anchor from Kontani *et al.* (2016).

the concrete cylinder specimens in compression. The tendencies are consistent with previous studies such as Bennett and Muir (1967), Award and Hilsdorf (1974), and Bocca and Cwti (2003).

Ballatore and Bocca (1997) stated that dynamic loading reduces pore space in the concrete so that in the subsequent static compressive tests deformability is hindered by improved material compaction, and that strain hardening takes place all the same as is reflected in an increase in maximum load and reduced deformability. Comparing Kontani *et al.* (2016) and Ballatore and Bocca (1997), both studies show similar strength increase of the cylindrical specimens, but different deformation behavior. Bocca and Cwti (2003) stated that the test pieces subjected to preloading yielded more homogenous results, with a reduction in standard deviation, compared to non-preloaded test pieces probably because of a decrease in the stress peaks occurring in the material and a redistribution of stresses due to cyclic load induced creep.

The residual anchor strength after cyclic loading is equal to or greater than (by up to 17%) the static strength of the specimen without cyclic loading according to Kontani *et al.* (2016). This phenomenon shows a tendency similar to the results of the compression tests on the cylinder specimens after cyclic loading. An explanation similar to that for the increase in residual cylinder strength after cyclic loading could be applied to the increase in the residual anchor strength after cyclic loading. Cracks on the cone surface develop by pulling of the stud anchor. The increase in anchor strength after cyclic

loading is, according to Bocca and Cwti (2003), due to the decrease in stress peaks in the material and at the crack tips, and the redistribution of stresses due to creep induced by cyclic loading.

According to the test results performed by Kontani *et al.* (2016), cyclic loading increased the residual strength of the anchor specimens in tension as well as the cylinder specimens in compression. Regarding deformation, the cylinder specimens exhibited residual strain of around 250 micros with the maximum stress ratio of 0.33. On the other hand, no residual deformation was observed on the anchor specimens with the maximum stress ratio of 0.22, which means that the effect of decreasing stress singularities due to cyclic loading induced creep which seemed to work very well even with the lower maximum stress ratios.

4. Introduction of S-N curve

The fatigue phenomenon can be expressed using S-N curves as shown in Fig. 8. The S-N curves show the relation between the maximum stress ratio (linear axis) and the number of constant load cycles (logarithmic axis). There is a fatigue limit identified for the steel member as shown in Fig. 8(a). Therefore, no matter how many cycles of stress at or below the fatigue limit are applied to a defect-free steel member, no fatigue fracture will occur. On the other hand, since no fatigue limit is identified for the concrete so far according to Stemland *et al.* (1990), Lee and Barr (2004), Tóth *et al.* (2016), and Karr *et al.* (2017), the linear relationship is extended to the stress ratio of zero, as shown in Fig. 8(b).

The idea introduced in this paper is to evaluate long-term soundness of equipment supports by S-N curves. Although the number of load cycles due to vibrating equipment such as turbines and generators is very high during normal operation of a nuclear power plant, the stress acting as the cyclic load is very low and is equal to or less than allowable stress, and thus it should be possible to evaluate the soundness of equipment supports by the S-N curve for operation periods such as 60 years.

The S-N curve can be expressed in Equation (6) according to Kishitani and Nishizawa (1987) and JSCE (2017). Transforming Equation (6) gives Equation (7).

Fig. 7 Pullout displacement of anchor vs. number of load cycles from Kontani *et al.* (2016).

Fig. 8 Conceptual images of S-N curves (AIJ 2015).

Table 2 S-N curves of previous research from Kishitani and Nishizawa (1987).

Specimen shape	Min. stress ratio S_{min}^{*1}	Max. stress ratio S_{max}^{*1}	Y-axis Intercept ^{*2}	1/K in Eq.(7)	S_{max} to fatigue failure ^{*3}	X-axis intercept
prism	5	65 - 85	1.025	-6.369	62.4	16.1
prism	10	65 - 80	1.000	-5.495	65.4	18.2
cylinder	2	66 - 84	0.958	-4.673	66.3	20.5
prism	14 - 22	53 - 100	0.927	-4.292	65.7	21.6
cylinder	8.6	65 - 80	1.016	-5.236	68.3	19.4
cylinder	10.3	59 - 74	0.929	-5.051	61.1	18.4
				average	64.9	19.0

*1 : In % to static strength

*2 : $1 + \frac{\log N}{K} \cdot S_{min}$ in Equation (7)

*3 : The maximum stress ratio to fatigue failure at 2×10^6 load cycles in % of static strength

Equation (7) shows that increasing S_{min} increases fatigue life, as experimentally demonstrated by Stemland *et al.* (1990). Therefore, if S_{min} is assumed to be zero, the fatigue life can be lowered against the same maximum stress ratio, which will provide more conservative evaluation.

Kishitani and Nishizawa (1987) reviewed the fatigue tests on concrete cylinder or prism specimens and evaluated S-N curves in the form of Equation (7) as shown in **Table 2**. As can be seen, all curves but one will not intercept one on the Y-axis because each curve was evaluated to fit each set of experimental data. The situation does not seem appropriate for generalization of the S-N curve. Therefore, by setting zero to S_{min} , Equation (7) is simplified to Equation (8), which intercepts one on the Y-axis of the S-N curve.

Next, it is necessary to determine the constant K, which means the intercepting point on the X-axis. According to **Table 2**, the maximum stress ratio to fatigue failure at 2×10^6 load cycles is 65% of static strength, which gives 18 as constant K to provide Equation (9) for the compression fatigue of concrete specimens. The S-N curve of the anchor specimen can be found in Eligehausen, *et al.* (2006) and is expressed in Equation (10). The S-N curve for concrete can be found in JSCE (2017) and is expressed in Equation (11) with the lower stress ratio of zero. The reduction factor of 0.85 is introduced to account for long-term strength and so on. Equations (9), (10), and (11) are shown in **Fig. 9**.

Fig. 9 Various S-N curves.

$$\log N = K \cdot \frac{1 - S_{max}}{1 - S_{min}} \quad (6)$$

$$S_{max} = \left(1 + \frac{\log N}{K} \cdot S_{min} \right) - \frac{\log N}{K} \quad (7)$$

$$S_{max} = 1 - \frac{\log N}{K} \quad (8)$$

$$S_{max} = 1 - \frac{\log N}{18} \quad (9)$$

$$S_{max} = 1 - \frac{\log N}{20} \quad (10)$$

$$S_{max} = 0.85 \times \left(1 - \frac{\log N}{17} \right) \quad (11)$$

where S_{max} , S_{min} : Maximum and minimum stress ratio to static strength.

N: Number of load cycles to fatigue failure.

K: Constant.

5. Proposal of soundness evaluation method for equipment support

5.1 Introduction of S-N curve of plain concrete in compression

The number of fatigue data for the anchor specimens is very small compared with fatigue data of concrete specimens in compression. At the same maximum stress ratio, the S-N curve for the anchor specimens expressed by Equation (10) provides greater fatigue life than that for concrete specimens in compression by Equation (9). Moreover, the reduction factor of 0.85 is introduced to Equation (10) and its X intercept is reduced from 18 to 17 to yield Equation (11) for conservativeness in fatigue evaluation. In this paper, the soundness evaluation using Equation (11) is proposed because Equation (11) derived by JSCE (2016) is based on the investigation of the enormous body of test data, which is believed to increase reliability, and because Equation (11) provide shorter and

more conservative fatigue life than Equation (9).

Although the failure mode of the anchor specimens is very different from the concrete cylinder specimens in compression, the progress of fatigue cracking of the anchor specimens is more stable and slower than that of the cylindrical specimens in compression. Thus, because Equation (11) is reliable in terms of the amount of data considered and provides shorter and more conservative fatigue life than Equation (9), it is proposed for the soundness evaluation of equipment supports in this paper to employ Equation (11) for cylinder specimens in compression instead of Equation (9) for anchor specimens although the fatigue process might be a little faster in cylinder specimens in compression.

As shown in **Fig. 5**, the residual strength of the anchor tends to increase with larger numbers of load cycles even if the maximum stress level is low. In the proposed evaluation method, since the fatigue limit ratio is set to the constant value of 0.3, the fatigue limit load tends to increase.

As shown in **Fig. 6**, no residual deformation is observed in the equipment support even after 10 million load cycles. As shown in **Fig. 7**, pull-out displacement of the anchor specimen is constant at the maximum stress level and does not increase up to 10 million load cycles.

Ozbolt *et al.* (1999) and Eligehausen and Sawade (1989) observed that cracking started at about 25% of peak load from a series of tensile test results on anchor specimens and that crack growth was very stable even after cracking at the anchor head. This might be a reason why no residual deformation was observed and the deformation at the maximum stress level was constant up to 10 million cycles, as shown in **Figs. 6** and **7**.

The knowledge of the strength increase after cyclic loading, and of no residual deformation and constant deformation at the maximum stress level up to 10 million load cycles, as shown in **Figs. 5** to **7**, is not directly incorporated in the proposed evaluation method. However, it improves the understanding of anchor behaviors under different numbers of load cycles and shows the validity to the soundness evaluation.

Fig. 10 Safe region without fatigue failure (The reference strength to maximum stress ratio is the static strength, p_a , obtained by experiment, and the fatigue limit ratio is 0.3.).

5.2 Introduction of region without fatigue failure in S-N curve

According to JEAG (1991), the reduction coefficient for long-term allowable stress is 0.3 of the static strength. This means that the stresses acting on an equipment support are equal to or less than 0.3 of static strength during normal operation of the nuclear facility. The S-N curve expressed by Equation (11) is proposed for use for soundness evaluation.

The number of load cycles to be considered for each rotating machine can be obtained. In Japan, nuclear power plants can be operated for up to 60 years if a 20-year extension of the operating period is approved, so the target is 60 years. For example, turbine and generator that rotate at 1,800 rpm in the 60 Hz region in Japan will generate load cycles of 5.68×10^{10} for 60 years. The S-N curves and the number of load cycles for the turbine and generator are shown in **Fig. 10**. The shaded area is the region without anchor fatigue failure. As long as the cyclic loads acting on the equipment supports are within this region, no fatigue failure will occur before the operation period exceeds 60 years.

The equipment supports of rotating machines other than turbines and generators could be also evaluated by checking the number of load cycles expected during their lifetime with the proposed S-N curve. As long as the number of load cycles and the maximum stress ratio is within the shaded area in **Fig. 10**, the equipment supports can be regarded as sound for their lifetime.

6. Discussion

6.1 Fatigue limit to expected load cycles

The intersection of the S-N curve and the X-axis indicates the fatigue fracture of a concrete specimen or member. In reality, however, the fracture does not occur because the stress ratio is zero. Thus, it is considered that concrete also should have a fatigue limit although the stress ratio could be quite low for infinite load cycles. For conventional fatigue testing with loading frequency of 10 Hz, the fatigue data of concrete are available up to 1.5×10^7 cycles with the maximum stress ratio down to 0.60 in Lantsoght *et al.* (2016). Ultrasonic fatigue testing has been employed to obtain the fatigue properties of metals. The number of load cycles reached more than 2×10^{10} and the fatigue limits of some metals could be reevaluated according to Mayer (2016). Karr *et al.* (2017) introduced the ultrasonic fatigue test to concrete and the concrete specimens survived 2×10^9 cycles with stress ratio of 0.38 and loading frequency of around 20 kHz. Even with the ultrasonic fatigue test results for an enormous number of loading cycles, no clues regarding the fatigue limit of concrete were obtained, which is consistent with Stemland *et al.* (1990), Lee and Barr (2004) and Tóth *et al.* (2016). Since the experimental determination of concrete fatigue properties is very time consuming, it is considered reasonable to evaluate soundness by the S-N curve with a straight line.

Equation (11) was compared with the fib model code (fib 2010) to validate the proposed method. Equation (11) is shown in **Fig. 11** with S-N curves obtained from the fib model code with the minimum stress ratios of 0 and 0.2. The S-N curves have a concave shape. In the region where load cycles are more than 10^9 , Equation (11) provides more conservative fatigue life than the fib model code.

Stemland *et al.* (1990) performed the constant amplitude tests on concrete specimens and the test results showed that the fatigue life at lower $S_{\max}$ values tends to be longer than indicated by the linear relationship. They proposed a design formula to predict the relation between $S_{\max}$, $S_{\min}$, and N as shown in Equation (12), which can be transformed into Equation (13). The design formula is illustrated in **Fig. 12** with $S_{\min} = 0$ for Equation (13). The effect of the change in minimum stress ratio on the fatigue life were incorporated in the design formula. As can be seen in **Fig. 12**, the slope of the curve changes at $\log N = 6$. It was also proposed that $\log N$ greater than $\log N = 6$ should be multiplied by some reduction factor.

$$\log N = (12 + 16 \cdot S_{\min} + 8 \cdot S_{\min}^2) \cdot (1 - S_{\max}) \quad (12)$$

$$S_{\max} = 1 - \frac{\log N}{(12 + 16 \cdot S_{\min} + 8 \cdot S_{\min}^2)} \quad (13)$$

Tóth *et al.* (2016) proposed a fatigue model to predict fatigue life of undercut anchors even at very high numbers of load cycles. The model was proposed based on

Fig. 11 Comparison with fib model code.

Fig. 12 Schematic S-N diagram for fatigue of concrete in compression with fatigue limit according to Stemland *et al.* (1990).

the Paris law, test results, and analysis results. The model uses the energy dissipation that causes material degradation due to repeated loading, not the stress intensity factor in the Paris law. The model predicted the fatigue life very well and decreased the slope of the S-N curve with increasing load cycles at a very high number of load cycles. Tóth *et al.* (2016) also stated that no endurance limit can be observed, which corresponds to the expected concrete fatigue behavior.

According to Stemland *et al.* (1990), a fatigue limit does not exist from a fracture mechanic point of view because all stress variations contribute to the damage and failure is only a question of time. It should, however, be possible to speak about a fatigue limit for practical design, since most structures are exposed to a limited number of cycles during their lifetime. The S-N curves with fatigue limits at different minimum stress ratios are shown in **Fig. 12** with Equation (11).

According to the above discussion, it would be possible to define a fatigue limit ratio with a limited number of load cycles of nuclear facilities. The fatigue limit ratio of the turbine and generator for load cycles of 5.68×10^{10} for 60 years can be defined as 0.3 of the reference strength to maximum stress ratio.

6.2 Effective embedment depth ratio for shear load

Pallarés (2010) investigated the test data in shear in terms of an effective embedment depth ratio l_e/d . For the shear tests with normal weight concrete, more than 84% of the specimens failed in steel in the tests with embedment ratios of 4.5 and above, and more than 98% failed in steel with embedment ratios of 5.5 and above. According to Matsuzaki *et al.* (1984), the shear strength of the stud anchor with the effective embedment depth ratio of 5.0 and above is determined by the failure in steel not in concrete.

For example, the embedment depth ratio is evaluated to satisfy Equation (4) with concrete strength and Young's modulus of 30 MPa and 25 kN/mm², bolt yield strength of 215 N/mm², and diameters of anchor bolt and anchor head of 22 mm and 35 mm, respectively. The minimum embedment depth ratio for concrete failure is 4.2, which is consistent with Pallarés (2010) and Matsuzaki *et al.* (1984). With the above conditions, it is confirmed that the allowable shear force $psa1$ evaluated by Equation (1) is much greater than $psa2$ evaluated by Equation (2). For shear load, only Equation (3) needs to be considered as long as the embedment depth satisfies Equation (4).

6.3 Comparison between S-N curve and previous test data

Equation (11) is compared with fatigue test results collected by Lantsoght *et al.* (2016) in **Fig. 13**. The data with compressive strength of 100 MPa or less and lower stress ratio of 0.3 or less were selected to validate the conservativeness of Equation (11). The number of data

was 191 and the maximum number of load cycles was 12 million. As can be seen from **Fig. 13**, Equation (11) provides safe evaluation for the entire data.

Equation (11) is compared with the ultrasonic fatigue test results performed by Karr *et al.* (2017) in **Fig. 13**. The maximum number of load cycles is 2.6×10^9 , which can never be reached in a conventional fatigue test. Fatigue test data and fitting curves of two series of specimens with strength of 80 MPa and 107 MPa are plotted in **Fig. 13**. The fatigue life obtained from the ultrasonic tests was apparently smaller than that from Equation (9), which is kind of an averaged S-N curve. The reason for this could be the shape of the specimen tested. Specimens 21 mm in diameter and 151 mm in length with steel rods connected at both ends were employed in order to cause resonance. The specimens were obtained from the concrete block. These might be the reasons for the shorter fatigue life. However, Equation (11) provides a fair evaluation to the ultrasonic fatigue data as well.

6.4 Determination of reference strength to maximum stress ratio

So far, the maximum stress ratio is defined relative to the static strength of the anchor specimens. The fatigue limit ratio is set at 0.3 as shown in **Fig. 10**. As long as the static strength is obtained by the experiments of the anchor specimens, the conditions described in **Fig. 10** are valid.

There are many test data on the static strength of the anchor specimens considering the edge effect and multiple anchor effect. According to AIJ (2010), two thirds of the cone failure strength p_{ta} from Equation (1) almost corresponds to the lower limit of the experimental data collected. Two thirds of the shear strength p_{sa} from Equation (3) also corresponds to the lower limit of the experimental data collected. The static strength of the anchors of existing equipment supports of nuclear facilities cannot be obtained by experiment and should be evaluated by the equations from AIJ (2010). Thus, the maximum stress ratio should be defined by two thirds of the static strength, $(2/3) \cdot p_a$, evaluated by the equations from AIJ (2010) for conservative evaluation, as described in **Fig. 14**.

This discussion is extremely important for defining the S-N curve. As shown in Equation (14), the reference

strength to maximum stress ratio should be defined by two thirds of the static strength, $(2/3) \cdot p_a$, from AIJ (2010) for conservative evaluation instead of the static strength of p_a . As a result, the fatigue limit load is $0.2 \cdot p_a$, as shown in Equation (15). However, the fatigue limit ratio to the reference strength is the same as 0.3.

The static strength of equipment supports of turbines and generators is evaluated by the equations from AIJ (2010), and two thirds of the static strength, $(2/3) \cdot p_a$, is the reference strength to maximum stress ratio. The long-term design load acting on equipment supports can be obtained from the design process due to rotation force and vibration amplitude of rotating machine. If the long-term design load acting on the equipment support is less than the fatigue limit load of $0.2 \cdot p_a$, the equipment support can be considered to be sound for 60 years of operation.

The combined force of the anchor bolt can be checked by Equation (16), which is the same formula with a different constant on the right side of the equation. The constant is the square of the fatigue limit ratio, which is 0.04 for the soundness evaluation of equipment supports. If the tensile load p and the shear load q acting on the equipment support are less than the fatigue limit and if p and q satisfy Equation (16), the support can be regarded sound for 60 years.

$$\text{Reference strength to maximum stress ratio} = (2/3) \cdot p_a \quad (14)$$

$$\text{Fatigue limit load} = 0.3 \times (2/3) \cdot p_a = 0.2 \cdot p_a \quad (15)$$

$$\left\{ \frac{p}{p_{ta}} \right\}^2 + \left\{ \frac{q}{p_{sa}} \right\}^2 \leq (\text{fatigue limit ratio})^2 = 0.04 \quad (16)$$

where p_a : Allowable force of p_{ta} or p_{sa} according to AIJ (2010).

p_{ta} , p_{sa} : Allowable tension force from Equation (1) and shear force from Equation (3) with reduction factor $k=1$.

6.5 Further development of soundness evaluation methods

Equation (11) with the maximum stress ratio of 0.3 yields the fatigue life of 10^{11} , which corresponds to 106 years of operation for the turbine and generator in the 60 Hz region in Japan. Therefore, the proposed evaluation method can be applied to up to 100 years of operation, beyond the 80 years designated by the subsequent license renewal (NUREG 2017) in the United States. In addition, the proposed method can be applied to load cycles longer than 100 years if the maximum stress ratio is reduced so that it is within the shaded area in **Fig. 10**.

The proposed method can also be applied to other types of anchors than stud anchors by collecting experimental results and analyzing them.

On the other hand, if the stress ratio is increased over 0.3, residual deformation and stiffness reduction might

Fig. 13 Comparison with fatigue test data.

occur in equipment supports due to load cycles. It is necessary, in this case, to confirm by experiment that there is no problem if the stress ratio exceeds 0.3.

7. Conclusions

A soundness evaluation method for equipment supports consisting of anchors using the S-N curve of plain concrete specimens in compression is proposed. If the static strength is obtained by experiment, the reference strength can be the static strength and the fatigue limit ratio is 0.3, as shown in Fig. 10.

If the static strength is evaluated by the equations from AIJ (2010), the reference strength should be two thirds of the static strength, $(2/3) \cdot P_a$, and the fatigue limit load is $0.2 \cdot P_a$, however, the fatigue limit ratio remains 0.3 as shown in Fig. 14. For the soundness evaluation of existing equipment supports, the strengths of the equipment supports can be evaluated by the equations from AIJ (2010) and cannot be obtained by experiment, therefore, the conditions described in Fig. 14 should be applied.

The static strength of the equipment supports of turbines and generators is evaluated by the equations from AIJ (2010) and two thirds of the static strength, $(2/3) \cdot P_a$, is the reference strength to maximum stress ratio. The long-term design load acting on equipment supports can be obtained from the design process due to the rotation force and vibration amplitude of the rotating machine. If the long-term design load acting on an equipment support is less than the fatigue limit load of $0.2 \cdot P_a$, the equipment support can be regarded sound for 60 years of operation.

The equipment supports of rotating machines other than turbines and generators could be also evaluated by checking the number of load cycles expected during their lifetime with the proposed S-N curve. As long as the number of load cycles and maximum stress ratio are within the shaded area in Fig. 14, the equipment supports can be regarded sound for their lifetime.

According to AIJ (2015), the degradation state of

equipment supports cannot be identified until cracks are visually detected as degradation phenomena for machine vibration. As a remedy, the method proposed in this paper allows the long-term soundness evaluation of equipment supports in a practical manner, which will increase the reliability of the machines. The proposed method will be reflected to “AIJ Guidelines for Maintenance and Management of Structures in Nuclear Facilities,” in the next revision.

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Fig. 14 Safe region without fatigue failure (The reference strength to maximum stress ratio is two thirds of the static strength, $(2/3) \cdot P_a$, evaluated by the equations from AIJ (2010), fatigue limit load is $0.2 \cdot P_a$ and fatigue limit ratio remains 0.3).

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Appendix : Fatigue of reinforced concrete structure

The reduction factors of concrete material or structural members are proposed based on a number of test results subjected to stepwise increases of cyclic loading level simulating an earthquake. For short-term allowable load for equipment supports, the reduction factors of Equation (1) are 2/3 and 0.6 according to AIJ (2010) and JEAG (1991), respectively. In the case where the in-plane shear strain due to earthquakes is significantly large in a reinforced concrete wall, reduction factors corresponding to shear strains have been introduced for the design of supports for equipment and piping as shown in **Fig. 15**, according to JEAG (1991). In this way, the effects of low cycle fatigue due to earthquakes are considered in designing structures.

The strength reduction due to high cycle fatigue is considered in designing structures such as reinforced concrete girders subjected to repeated loading and reinforced concrete slabs under moving wheel load according to JSCE (2017). The fatigue strength of concrete is evaluated using Equation (6) for load cycles of 2×10^6 or less and the Miner's law is applied for variations in the maximum stress ratio.

The proposed evaluation method in this paper deals

with the soundness evaluation of existing equipment supports under ultra-high cycle fatigue. The same concept is not applied to designing equipment supports at this time. The load cycles due to machine vibration are on the order of ten to the tenth power with constant amplitude. The soundness of the equipment support is evaluated by extrapolating to the tenth power order using Equation (11), which is derived by removing the term of the minimum stress ratio from Equation (6).

Fig. 15 Allowable area for in-plane shear strain and out-of-plane tensile force (modified and translated according to JEAG 1991).