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Outline of the seismic buckling design guideline of FBR main vessels

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ABSTRACT: Central Research Institute of Electric Power Industry(CRIEPI, JAPAN), commissioned by the Ministry of International Trade and Industry, is carrying out the Demonstration Test and Research Program of Buckling of FBR (FY 1987 - FY 1996). Phase-I,-II was finished after establishing a seismic buckling design guideline - a draft - in FY 1993. The purpose of this paper is to describe the outline of the rationalized buckling design guideline for seismic loadings. This guideline provides seismic stability criteria for determining the structural adequacy against shear-bending buckling of short cylindrical shells.

INTRODUCTION[1]

In Japan, nuclear reactor facilities are designed to withstand maximum design earthquakes S1, and extreme design earthquakes S2. The target of the seismic design for the most important facility in a nuclear power plant is to avoid critical damage while keeping structures in the elastic range against S1 although the plastic state is allowed against S2.

It is necessary to apply similar design procedures to FBR main vessels and to establish a more concrete target for the seismic buckling design. It is reasonable that the design target relative to seismic motion S1 is to keep main vessels in the elastic range. In establishing a design target relative to S2, it is important to suppose critical damage to main vessels.

With the base-isolated building method employed, the horizontal seismic force applied to main vessels may be recognized as static loading. For horizontal seismic motion, therefore, occurrence of buckling means that the limit state is arrived. In conventional reactor buildings, on the other hand, occurrence of buckling does not mean the arrival of the limit state, because the total energy brought to the structure by seismic motion is finite and the structure's deformation can remain within a certain range by the energy absorption capability of the structure in the pre- and post-buckling stage. If the deformations should grow enough after the occurrence of buckling, however, local strain at the buckling wrinkle area may exceed the low cycle fatigue limit and control rod insertion will not always be possible. Taking into account these points, the limit state of FBR main vessels in conventional reactor buildings should be determined.

With the above-mentioned points of view summarized, the design target relative to seismic motion S2 is to be established as follows :

(a) No buckling should be allowed to take place.

(b) Main vessels must secure a certain level of seismic margin f to the limit state.

- Conventional reactor building : $f \geq 1.5$ to the limit state
- Base-isolated reactor building : $f \geq 1.5$ to the buckling occurrence

SEISMIC BUCKLING DESIGN GUIDELINE OF FBR MAIN VESSELS -A DRAFT-

1. GENERAL PROVISIONS

1.1 SCOPE

This guideline provides criteria of seismic stability for determining the structural adequacy against dynamic buckling of Demonstration and Commercial FBR main vessels when subjected to horizontal and vertical seismic loads acting independently or in combination. The buckling formulae and design considerations contained herein are based on the latest test data, and payed attention to the same level of safety as other relevant codes and standards. The research leading to the development of the criteria is documented in the commentary.

1.2 NOMENCLATURE

A : Cross sectional area of cylindrical shell
C : Response amplification factor specified in **2.4**
D_s : Response reduction factor specified in **2.3**
E : Young's modulus (See Table 1.2)
F_0 : Axial force due to dead load
F_1 : Axial force due to vertical S1 earthquake calculated by linear seismic response analysis
F_2 : Axial force due to vertical S2 earthquake calculated by linear seismic response analysis
F_{al} : Allowable axial compression force specified in **4.2.3**
H : Height of load application point from root of cylinder
L : Length of cylinder
M_1 : Bending moment due to S1 earthquake calculated by linear seismic response analysis
M_2: Bending moment due to S2 earthquake calculated by linear seismic response analysis
M_{al}: Allowable bending moment specified in **4.2.2**
Q_1: Horizontal shear force due to S1 earthquake calculated by linear seismic response analysis
Q_2: Horizontal shear force due to S2 earthquake calculated by linear seismic response analysis
Q_{al}: Allowable transverse shear load specified in **4.2.1**
Q_{cr}: Horizontal buckling load
R : Radius of cylinder
$S_A(T)$: Value at period T of the acceleration response spectrum for the horizontal seismic motion under design condition
$_vS_A(T)$: Value at period T of the acceleration response spectrum for the vertical seismic motion under design condition
Sy : Design yield stress (σ_y or 0.2% proof stress ; See Table 1.1)
T_0 : Fundamental natural period of the structure regarding horizontal vibration
T_v: Fundamental natural period of the structure regarding vertical vibration

W : Imperfection amplitude
Z : Section modulus of cylindrical shell
ZPA: Zero period acceleration
f : Seismic margin
ℓ_g : Gauge length
t : Shell thickness
α_1 : Load safety factor relative to S1 specified in **2.5**
α_2 : Load safety factor relative to S2 specified in **2.5**
δ_{cr}: Horizontal displacement when buckling occurs
δ_e : Horizontal displacement when the elastic system's restoring force reaches the level of buckling load
δ_u : Horizontal displacement when a structure reaches the limit state
λ : $(S_y/E)(R/t)$
$\mu = \delta_{cr} / \delta_e$: Nonlinearity factor specified in **2.3.3**
ν_c : A strength safety factor for axial compression buckling specified in **4.2.4**
ν_b : A strength safety factor for bending buckling buckling specified in **4.2.4**
ν_s : A strength safety factor for shear buckling buckling specified in **4.2.4**
$\sigma^e_{b,cr}$: Elastic bending buckling stress
$\sigma^p_{b,cr}$: Elastic-plastic bending buckling stress
$\sigma^e_{a,cr}$: Elastic axial buckling stress
$\sigma^p_{a,cr}$: Elastic-plastic axial buckling stress
τ^e_{cr} : Elastic shear buckling stress
τ^p_{cr} : Elastic-plastic shear buckling stress

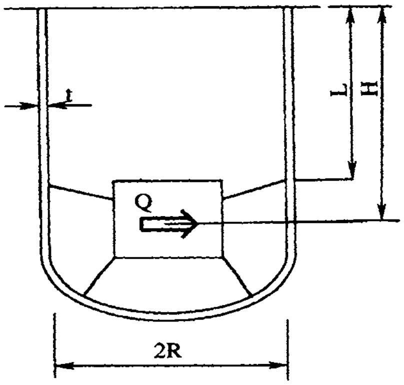
1.3 Limitations

This guideline can be applied to those main vessels which satisfy **1.3.1 ~ 1.3.4.**

1.3.1 Structural Shape

This guideline is applicable to cylindrical shells with the following parameters :

(1) Radius to thickness ratio : $50 \leq R/t \leq 400$
(2) Length to radius ratio : $1.0 \leq L/R \leq 5.0$
(3) Height of load application point from root to radius ratio : $1.0 \leq H/R \leq 5.0$



1.3.2 Thermal Conditions

This guideline is applicable to the range of temperatures conceivable (~ 650°C) in fast breeder reactors.

1.3.3 Materials

The main vessels are produced by austenitic stainless steel, Type-304 or -316.
(1) See Table 1.1 for design yield stress[3].
(2) See Table 1.2 for modulus of elasticity[3],[4].

1.3.4 Load Conditions

Load specified herein is earthquake force. Load combinations with other loads shall be handled as provided in "Class 1 Components of seismic Class As, Technical Guidelines for Aseismic Design of Nuclear Power Plants (JEAG4601)[2] ".

1.4 Seismic Buckling Design Method

Seismic stability assessment of the main vessels can be achieved in accordance with the flow chart shown in Fig. 1.1 after proper modeling of an actual structure.

2 CRITERIA OF SEISMIC STABILITY

2.1 General

Specified in **2.2** ~ **2.5** are the seismic stability assessment methods of cylindrical shell structures to prevent the occurrence of buckling. Moreover, **2.6** specifies the seismic margin evaluation procedure to the limit state.

2.2 Basic Criteria for Seismic Stability Assessment

Main vessels located in conventional and base-isolated reactor buildings shall be assessed for their seismic stability in accordance with the criteria specified below. In the case of conventional reactor buildings, a combination of horizontal and vertical seismic forces with short period components shall be evaluated at the energy input level. In the case of base-isolated buildings, on the other hand, the superposition effect shall be evaluated at the induced stress level.

Based on the shear and bending buckling data of cylindrical shells specified in **1.3**, interaction relation of the fifth power is adopted.

2.2.1 Conventional Reactor Building

(1) Horizontal seismic load

Seismic motion S1 :

$$\left\{D_sC\alpha_1\frac{Q_1}{Q_{al}}\right\}^5+\left\{\frac{D_sC\alpha_1M_1}{M_{al}}+\frac{F_0}{F_{al}}\right\}^5<1 \qquad (F_0\geq 0 : (\text{ Compressive force }))$$

$$\left\{D_sC\alpha_1\frac{Q_1}{Q_{al}}\right\}^5+\left\{\frac{D_sC\alpha_1M_1+\frac{Z}{A}F_0}{M_{al}}\right\}^5<1 \qquad (F_0<0 : (\text{ Tensile force }))$$

where $D_sC \leq 1$,

If $F_0 > 0.3\ F_{al}$, $D_sC = 1$

If $F_0 \leq 0.3\ F_{al}$ and $D_sC\ \alpha_1 < 1$, $D_sC\ \alpha_1 = 1$

Seismic motion S2 :

$$\left\{D_sC\alpha_2\frac{Q_2}{Q_{al}}\right\}^5+\left\{\frac{D_sC\alpha_2M_2}{M_{al}}+\frac{F_0}{F_{al}}\right\}^5<1 \qquad (\,F_0\geq 0:(\text{ Compressive force }))$$

$$\left\{D_sC\alpha_2\frac{Q_2}{Q_{al}}\right\}^5+\left\{\frac{D_sC\alpha_2M_2+\frac{Z}{A}F_0}{M_{al}}\right\}^5<1 \qquad (\,F_0<0:(\text{ Tensile force }))$$

where $D_sC \leq 1$,
If $F_0 > 0.3\ F_{al}$, $D_sC = 1$

(2) Vertical seismic load
Seismic motion S1 (in the case of $F_0 + \alpha_1\ F_1 > 0$)

$$\left(\frac{F_0+\alpha_1\ F_1}{F_{al}}\right)^2+\left(\frac{D_s\ C\ \alpha_1M_1}{M_{al}}\right)^2<1$$

where $D_sC \leq 1$,
If $F_0 > 0.3\ F_{al}$, $D_sC = 1$
If $F_0 \leq 0.3\ F_{al}$ and $D_sC\ \alpha_1 < 1$, $D_sC\ \alpha_1 = 1$

Seismic motion S2 (in the case of $F_0 + \alpha_2\ F_2 > 0$)

$$\left(\frac{F_0+\alpha_2\ F_2}{F_{al}}\right)^2+\left(\frac{D_s\ C\ \alpha_2M_2}{M_{al}}\right)^2<1$$

where $D_sC \leq 1$,
If $F_0 > 0.3\ F_{al}$, $D_sC = 1$

2.2.2 Base-isolated Reactor Building

Seismic motion S1 :

$$\left\{\alpha_1\frac{Q_1}{Q_{al}}\right\}^5+\left\{\frac{\alpha_1M_1}{M_{al}}+\frac{F_0+\alpha_1F_1}{F_{al}}\right\}^5<1 \qquad (\,F_0+\alpha_1F_1\geq 0\,)$$

$$\left\{\alpha_1\frac{Q_1}{Q_{al}}\right\}^5+\left\{\frac{\alpha_1M_1+\frac{Z}{A}(F_0+\alpha_1F_1)}{M_{al}}\right\}^5<1 \qquad (\,F_0+\alpha_1F_1<0\,)$$

Seismic motion S2 :

$$\left\{\alpha_2\frac{Q_2}{Q_{al}}\right\}^5+\left\{\frac{\alpha_2M_2}{M_{al}}+\frac{F_0+\alpha_2F_2}{F_{al}}\right\}^5<1 \qquad (\,F_0+\alpha_2F_2\geq 0\,)$$

$$\left\{\alpha_2\frac{Q_2}{Q_{al}}\right\}^5+\left\{\frac{\alpha_2M_2+\frac{Z}{A}(F_0+\alpha_2F_2)}{M_{al}}\right\}^5<1 \qquad (\,F_0+\alpha_2F_2<0\,)$$

where A : Cross sectional area of cylindrical shell
C : Response amplification factor specified in **2.4**
D_s : Response reduction factor specified in **2.3**
F_0 : Axial force due to dead load
F_1 : Axial force due to vertical S1 earthquake calculated by linear seismic response analysis
F_2 : Axial force due to vertical S2 earthquake calculated by linear seismic response analysis
F_{al}: Allowable axial compression force specified in **4.2.3**
M_1: Bending moment due to S1 earthquake calculated by linear seismic response analysis
M_2: Bending moment due to S2 earthquake calculated by linear seismic response analysis
M_{al}: Allowable bending moment specified in **4.2.2**
Q_1 : Horizontal shear force due to S1 earthquake calculated by linear seismic response analysis
Q_2 : Horizontal shear force due to S2 earthquake calculated by linear seismic response analysis
Q_{al} :Allowable transverse shear load specified in **4.2.1**
Z : Section modulus of cylindrical shell
α_1 : Load safety factor relative to S1 specified in **2.5**
α_2 : Load safety factor relative to S2 specified in **2.5**

2.3 Response Reduction Factor

The response reduction factor shall be used to simply and quantitatively evaluate the response reduction due to the effect of plasticity before the occurrence of buckling under horizontal seismic loading.

2.3.1 Definition

If Q is the imaginary load evaluated by the linear analysis under critical horizontal input acceleration to cause buckling, response reduction factor D_s may be defined by the following equation :

$$D_s = \frac{Q_{cr}}{Q}$$

where Q_{cr} : Actual horizontal buckling load

2.3.2 Evaluation of Response Reduction Factor

The response reduction factor may be simply obtained from the equations given below.

$$D_s = \begin{cases} \dfrac{1}{\mu} & ; \text{ in the case of } \dfrac{S_A(T_0)}{ZPA} \geq 2\mu \\[2ex] 2\dfrac{ZPA}{S_A(T_0)} & ; \text{ in the case of } 2 < \dfrac{S_A(T_0)}{ZPA} < 2\mu \\[2ex] 1 & ; \text{ in the case of } \dfrac{S_A(T_0)}{ZPA} \leq 2 \end{cases}$$

where $\mu = \delta_{cr} / \delta_e$: Nonlinearity factor specified in **2.3.3**

$S_A(T)$: Value at period T of the acceleration response spectrum for the horizontal seismic motion under design condition

T_0 : Fundamental natural period of the structure regarding horizontal vibration

ZPA: Zero period acceleration

2.3.3 Nonlinearity Factor

Nonlinearity factor μ is defined by the following equation :

$$\mu = \frac{\delta_{cr}}{\delta_e}$$

μ can be evaluated by the following empirical formula.

$$\mu = 1 + 1.5 \exp(-8\lambda)$$

where δ_{cr}: Horizontal displacement when buckling occurs

δ_e : Horizontal displacement when the elastic system's restoring force reaches the level of buckling load

λ : $(S_y/E)(R/t)$

Sy : Design yield stress (σ_y or 0.2% proof stress)

E : Young's modulus

2.4 Response Amplification Factor Related to Vertical Seismic Load

The response of a structure shall be evaluated as the value of multiplying the response under horizontal seismic load by the amplification factor related to vertical seismic load. The amplification factor shall be determined by the following formula considering the increase of input energy due to vertical seismic load.

$$C = \sqrt{1 + \left[\frac{T_v \, {}_vS_A(T_v)}{T_0 \, S_A(T_0)}\right]^2}$$

where C : Response amplification factor

$S_A(T)$: Value at period T of the acceleration response spectrum for the horizontal seismic motion under design condition

${}_vS_A(T)$: Value at period T of the acceleration response spectrum for the vertical seismic motion under design condition

T_0 : Fundamental natural period of the structure regarding horizontal vibration

T_v : Fundamental natural period of the structure regarding vertical vibration

2.5 Load Safety Factor

This factor is adopted to assure that no buckling will occur against the load multiplied by the load safety factor. α_1 shall be taken for seismic motion S1 and α_2 for seismic motion S2, with the following numerical values applied :

	α_1(seismic motion S1)	α_2(seismic motion S2)
Conventional reactor building	1.5	1.0
Base-isolated reactor building	1.5	1.25

2.6 Evaluation of Seismic Margin

2.6.1 General

When a conventional reactor building is employed, seismic margin relative to seismic motion S2 shall be evaluated in accordance with the procedure specified below to secure a certain level of seismic margin to the limit state, in addition to the design procedure to assess the seismic stability specified in **2.2 ~ 2.5**.

2.6.2 Seismic Margin

Seismic Margin f relative to the limit state of a structure shall be defined by the following expression :

$$f = \frac{\text{the seismic input level when a structure reaches the limit state}}{\text{the seismic input level of a design earthquake motion}}$$

The limit state of a structure shall be determined as that where the horizontal relative displacement of the cylindrical part of a main vessel reaches δ_u given by the following equation :

$$\delta_u = \min.\left\{ 2\delta_{cr}, 5\delta_e \right\}$$

At this limit state, a seismic margin of 1.5 or more shall be taken.

3 EVALUATION OF LINEAR SEISMIC RESPONSE

Evaluation of linear seismic response follows the current methods provided in "Class 1 Components of seismic Class As, Technical Guidelines for Aseismic Design of Nuclear Power Plants (JEAG4601)[2] ".

4 EVALUATION OF ALLOWABLE BUCKLING STRENGTH

4.1 General

Buckling strength may be obtained by the formulae evaluating the allowable buckling strength specified in **4.2.** In this case, material properties shall apply as determined at the maximum temperature of the structure during normal operation. The buckling strength may also be obtained through the finite element elastic-plastic large displacement analyses by the use of reasonable numerical models. In that case, however, the accuracy of results must be verified.

4.2 Formulae for Evaluating Allowable Buckling Strength

The formulae given below shall be used to evaluate the allowable buckling strength related to shearing, bending and axial compression loads. These formulae are established, based on numerous experiments conducted for all shapes, material and temperature conditions conceivable in a fast breeder reactor.

4.2.1 Allowable Shear Buckling Strength

$$Q_{al}=\tau_{cr}^{p}\pi Rt\frac{1}{\nu_s}$$

where

$$\frac{\tau_{cr}^{p}}{\tau_{cr}^{e}}+\left(\frac{\sqrt{3}\,\tau_{cr}^{p}}{1.27Sy}\right)^2=1$$

$$\tau_{cr}^{e}=0.8\,\frac{4.82}{\left(\frac{L}{\sqrt{Rt}}\right)^2}\sqrt{1+0.0239\left(\frac{L}{\sqrt{Rt}}\right)^3}\,\frac{Et}{R}$$

where ν_s : A strength safety factor for shear buckling specified in **4.2.4**

τ_{cr}^{e} : Elastic shear buckling stress

τ_{cr}^{p} : Elastic-plastic shear buckling stress

4.2.2 Allowable Bending Buckling Strength

$$M_{al}=\sigma_{b,cr}^{p}\pi R^2t\frac{1}{\nu_b}$$

where

$$\frac{\sigma_{b,cr}^{p}}{\sigma_{b,cr}^{e}}+\left(\frac{\sigma_{b,cr}^{p}}{1.27Sy}\right)^2=1$$

$$\sigma_{b,cr}^{e}=0.6\left[1-0.731\times\left\{1-\exp\left(-\frac{1}{16}\sqrt{\frac{R}{t}}\right)\right\}\right]\frac{Et}{R}$$

where ν_b : A strength safety factor for bending buckling specified in **4.2.4**

$\sigma_{b,cr}^{e}$: Elastic bending buckling stress

$\sigma_{b,cr}^{p}$: Elastic-plastic bending buckling stress

4.2.3 Allowable Axial Buckling Strength

$$F_{al}=\sigma_{a,cr}^{p}2\pi Rt\frac{1}{\nu_c}$$

where

$$\frac{\sigma_{a,cr}^{p}}{\sigma_{a,cr}^{e}}+\left(\frac{\sigma_{a,cr}^{p}}{Sy}\right)^2=1$$

$$\sigma_{a,cr}^{e}=0.6\left[1-0.901\times\left\{1-\exp\left(-\frac{1}{16}\sqrt{\frac{R}{t}}\right)\right\}\right]\frac{Et}{R}$$

where ν_c : A strength safety factor for axial compression buckling specified in **4.2.4**

$\sigma_{a,cr}^{e}$: Elastic axial buckling stress

$\sigma_{a,cr}^{p}$: Elastic-plastic axial buckling stress

4.2.4 Strength Safety Factor

ν_s ν_b and ν_c represent safety factors relating to the buckling strength of the structure. They shall take identical values for both seismic motions S1 and S2, and apply those values specified below, which have been established in relation to the formulae for evaluating the allowable buckling strength, with consideration of the scattered irregularities in shapes, materials and shape imperfections.

Buckling Mode	Shear	Bending	Axial Compression
	ν_s	ν_b	ν_c
Strength safety factors	1.2	1.5	1.5

5 INITIAL IMPERFECTION

5.1 Imperfection Amplitude

The maximum shape imperfection assumed in **4.2**, for manufacturing actual FBRs, shall take a value specified below.

Local deviation from true circular shape W :

Shear buckling : $W \leq t$

Bending buckling : $W \leq 0.5\,t$

where gauge length ℓ_g on peak-to-peak basis are as follows :

Circumferential direction : $\ell_g = 2\,(R\,t)^{0.25} L^{0.5}$

Axial direction : $\ell_g = 4\,(R\,t)^{0.5}$

5.2 Buckling Strength Correction Factors

Buckling strength given by **4.2** can be applicable within the imperfection defined in **5.1** If such imperfections should exceed the specified values, it shall be necessary to properly reduce the allowable buckling strength obtained by the formulae. Buckling strength correction factors shown in Fig.5.1 are available for the proper reduction of the allowable buckling strength.

REFERENCES

[1] Akiyama, H. et al.: Outline of the seismic buckling design guideline of an FBR - a tentative draft, Nuclear Engineering and Design 140 (1993), 319-330

[2] The Japan Electric Association :Technical Guidelines for Aseismic Design of Nuclear Power Plants (JEAG4601) (1984)

[3] Power Reactor and Nuclear Fuel Development Corporation (Japan) : Elevated Temperature Structural Design Guide for Class 1 Components of Prototype Fast Breeder Reactor(ETSDG)

[4] Notification No. 501 of the Ministry of International Trade and Industry (Japan) (1986)

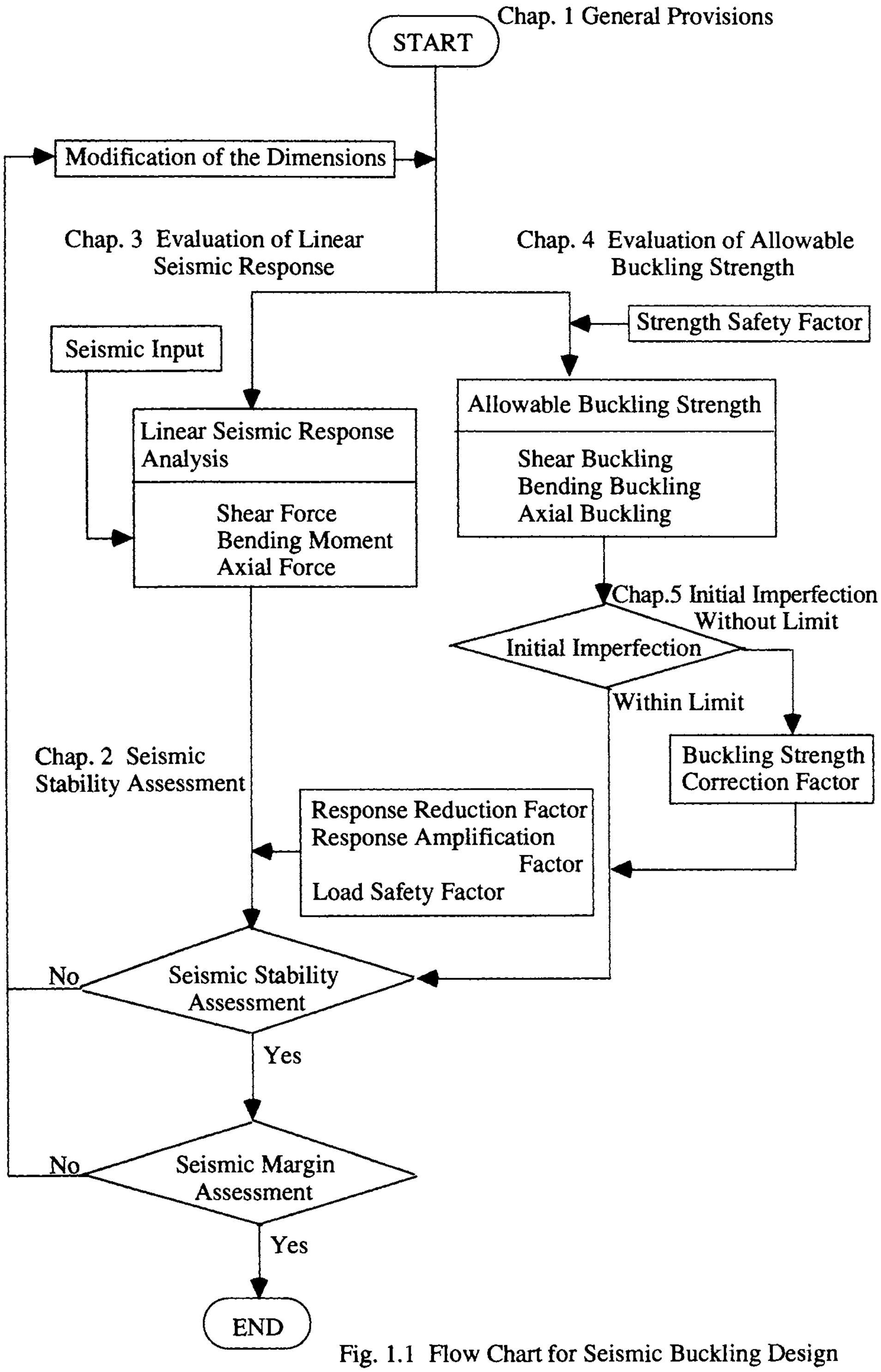


Fig. 1.1 Flow Chart for Seismic Buckling Design

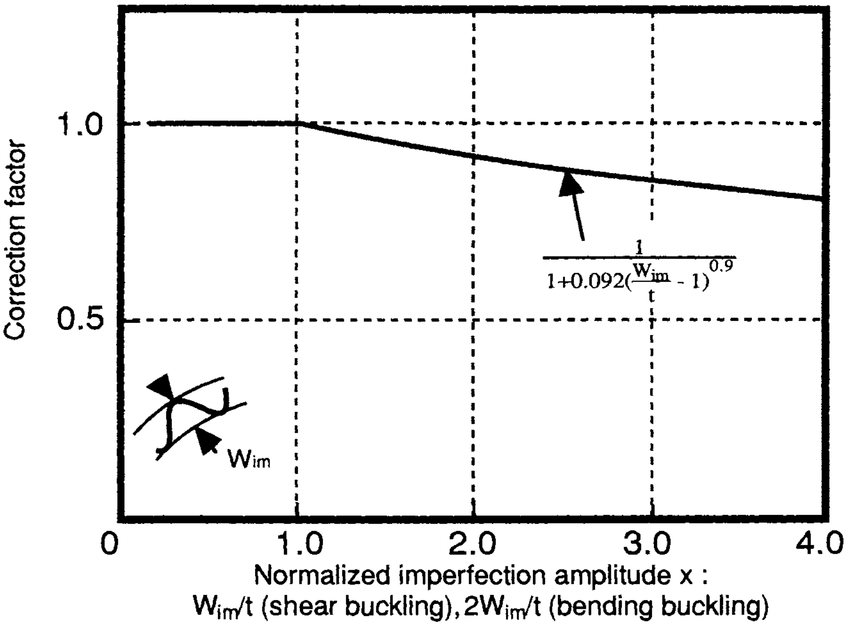


Fig. 5.1 Correction Factor of Buckling Load

Table 1.1 Design Yield Stress S_y (kg/mm^2)

Temperature (℃)	SUS304	SUS316
-30 ~ 40	21.0	21.0
75	18.7	19.1
100	17.4	17.9
150	15.8	16.4
200	14.7	15.2
225	14.2	14.7
250	13.8	14.2
275	13.4	13.8
300	13.0	13.4
325	12.7	13.1
350	12.6	12.9
375	12.4	12.7
400	12.1	12.5
425	11.8	12.4
450	11.6	12.1
475	11.3	11.9
500	11.1	11.8
525	11.0	11.6
550	10.8	11.4
575	10.6	11.3
600	10.4	11.1
625	10.2	10.9
650	10.0	10.7

Table 1.2 Young's Modulus E(kg/mm^2)

Temperature (℃)	SUS304, SUS316
20	19900
50	19700
75	19600
100	19400
125	19200
150	19000
175	18900
200	18700
225	18600
250	18400
275	18200
300	18000
325	17800
350	17600
375	17400
400	17200
425	17000
450	16700
475	16400
500	16200
525	15900
550	15700
575	15400
600	15200
625	14900
650	14700