# 第 四 章　　压力容器设计

# CHAPTER Ⅳ

# Design of Pressure Vessel

## 4.4 分析设计（ Design by Analysis ）

4.1 概述

4.2 设计准则

4.3 常规设计

4.4 分析设计

- 4.4.1 概述
- 4.4.2 压力容器的应力分类
- 4.4.3 应力强度计算
- 4.4.4 应力强度限制
- 4.4.5 分析设计的应用

4.5 疲劳分析

4.6 压力容器设计技术进展

# 4.4 Design by Analysis

**教学重点：**

压力容器的应力分类。

**教学难点：**

应力强度计算。

# 4.4 Design by Analysis

- **Design of pressure vessels**
  - **Design-by-rule**
    - **GB150《Steel Pressure Vessels》**
  - **Design-by-analysis**
    - **JB4732 《Steel Pressure Vessels—Code for Design by Analysis》**

# 4.4.1 Introduction

**Limitations of design-by-rule:**

## （1）Loadings

| Loadings | Design-by-rule | Design-by-analysis |
|---|---|---|
| Static | √ | √ |
| Cyclic | × | √ |

## （2）Stress calculation

| Stress calculation | Design-by-rule | Design-by-analysis |
|---|---|---|
| Methods | Simple formulas | Analytic, numerical, experimental method |
| Places | Shell | All points |

## Limitations of design-by-rule:

（3）Pressure vessel structures

| Codes | Design-by-rule | Design-by-analysis |
|---|---|---|
| Structures | Some structures | Any structures |

## Philosophy of design-by-analysis

（1）Different types of stress have different degrees of importance to pressure vessels;

（2）If a proper stress analysis can be conducted, a better, less conservative design of pressure vessels can be made.

# 4.4.2 Stress Categories of Pressure Vessels

## 4.4.2.1 Stress Categories

**Basis for stress category: hazards to pressure vessels**

**Determining factors: (1) location and distribution;**

**(2) types of loading**

**Major stress categories: primary, secondary, peak**

## Primary stress (*P*):

**Definition:** developed by the imposed loading;

necessary to satisfy the laws of equilibrium

between external and internal forces and moments

**Basic characteristic:** not self-limiting

**Sub-categories:** general primary membrane stress ($P_m$),

local primary membrane stress ($P_L$),

primary bending stress ($P_b$)

**Primary stress**

- **Membrane**
  - **General ($P_m$)**

    A general primary membrane is the one that is so distributed in the structure that no redistribution of load occurs as a result of yielding. An example is the stress in a circular cylindrical shell due to internal pressure.

  - **Local ($P_L$)**

    Examples of a local primary membrane stress are the membrane stress in a shell produced by external load and the moment at a permanent support or at a nozzle connection.

- **Bending ($P_b$)**

  An example is the bending stress in the central portion of a flat head due to pressure.

## Secondary stress ($Q$)

**Definition:** developed by the self-constrained of a structure

**Basic characteristic:** self-limiting

## Peak stress ($F$)

**Definition:** highest stress in the region under consideration

**Basic characteristic:** causing no significant distortion;

a possible source of fatigue failure

## Table 4-15 Classification of Stress for Some Typical Cases

| Vessel Component | Location | Origin of Stress | Type of Stress | Classification |
|---|---|---|---|---|
| Cylindrical or spherical shell | Shell plate remote from discontinuities | Internal pressure | General membrane<br>Gradient through plate thickness | $P_m$<br>Q |
| | | Axial thermal gradient | Membrane<br>Bending | Q<br>Q |
| | Junction with head or flange | Internal pressure | Membrane<br>Bending | $P_L$<br>Q |
| | Near nozzle or other opening | External load, moment or internal pressure | Membrane<br>Bending<br>Peak (fillet or corner) | $P_L$<br>Q<br>F |

## Table 4-15 Classification of Stress for Some Typical Cases

| Vessel Component | Location | Origin of Stress | Type of Stress | Classification |
|---|---|---|---|---|
| Dished head or conical head | Crown | Internal pressure | Membrane<br>Bending | $P_m$<br>$P_b$ |
| | Knuckle or junction to shell | Internal pressure | Membrane<br>Bending | $P_L$<br>$Q$ |
| Flat head | Center region | Internal pressure | Membrane<br>Bending | $P_m$<br>$P_b$ |
| | Junction to shell | Internal pressure | Membrane<br>Bending | $P_L$<br>$Q$ |

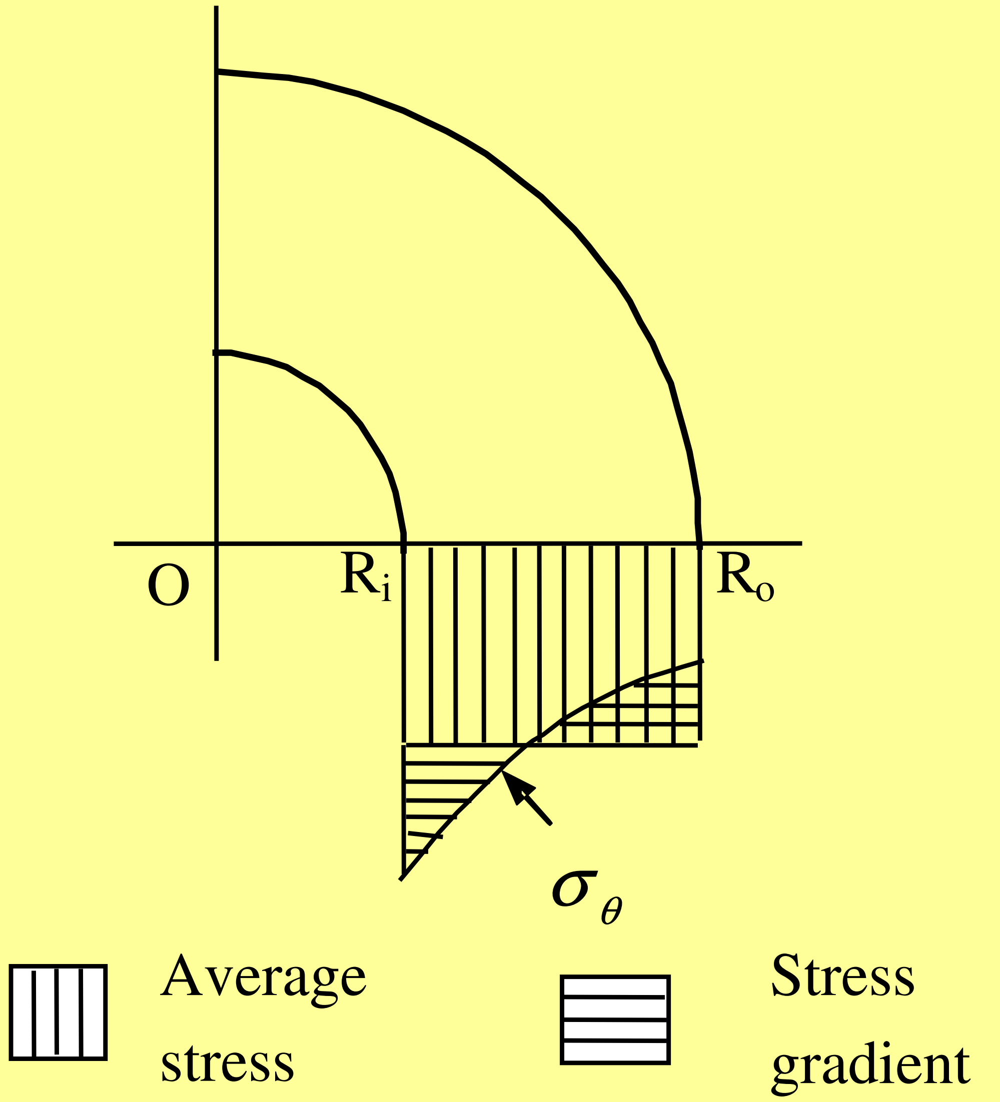



Fig .4-56 Decomposition of hoop stress in thick cylinder under internal pressure

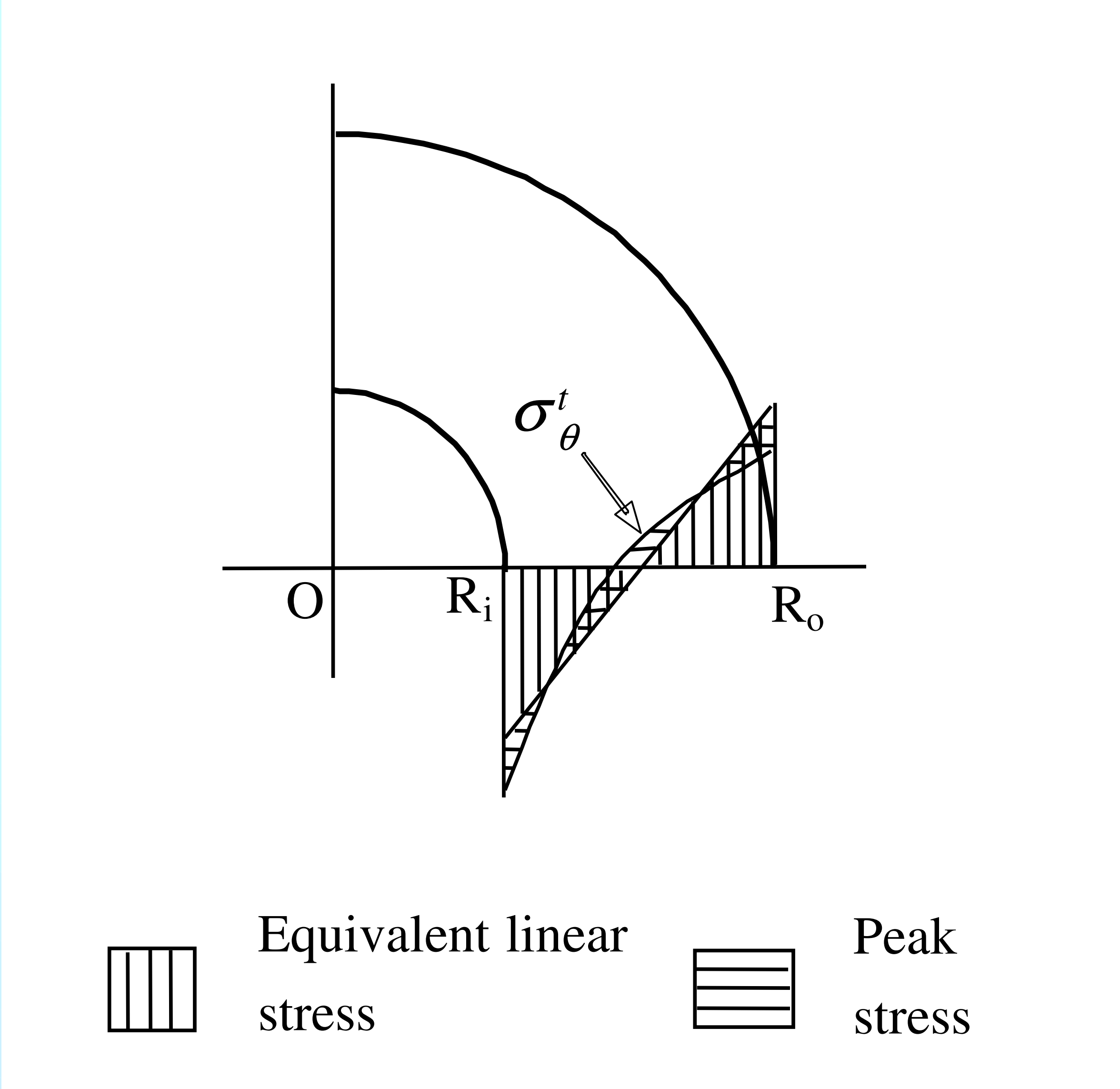



**Fig.4-57 Linearization of hoop thermal stress in thick cylinder heated externally**

# 4.4.3 Calculation of Stress Intensity

**Stress intensity:** difference between the largest principal stress and smallest principal stress

**Five stress intensities:** $S_I$ , $S_{II}$ , $S_{III}$ , $S_{IV}$ and $S_V$

(1) General primary membrane stress intensity $S_I$ ,

(2) Local primary membrane stress intensity $S_{II}$

(3) Primary membrane (general or local) plus primary bending stress intensity $S_{III}$

(4) Primary plus second stress intensity $S_{IV}$

(5) Peak stress intensity $S_V$

## Steps for stress intensity calculation:

(1) Choose a coordinate system with x, θ , z representing longitudinal direction, hoop direction and radial direction respectively. Denote normal stresses with $\sigma_x$, $\sigma_\theta$ and $\sigma_z$ and shear stresses with $\tau_{x\theta}$、$\tau_{xz}$、$\tau_{z\theta}$.

(2) Calculate stress components and categorize them into $P_m$, $P_L$, $P_b$, Q and F.

(3) Superpose stress components which belong the same category and obtain $P_m$ , $P_L$ , $P_L + P_b$ , $P_L + P_b + Q$ and $P_L + P_b + Q + F$.

## Steps for stress intensity calculation:

**(4) Calculate principal stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$, here $\sigma_1 > \sigma_2 > \sigma_3$.**

**(5) Calculate the maximum difference between principal stresses**

$$\sigma_{13} = \sigma_1 - \sigma_3$$

$\sigma_{13}$ **corresponding to** $P_m$ , $P_L$, $P_L + P_b$, $P_L + P_b + Q$ , $P_L + P_b + Q + F$ **is the stress intensity** $S_I$ , $S_{II}$ , $S_{III}$ , $S_{IV}$ **and** $S_V$ **respectively.**

# 4.4.4 Limit of Stress Intensities

**Design stress intensity :**

$$S_m = \min\left(\frac{\sigma_s}{n_s},\ \frac{\sigma_s^t}{n_s^t},\ \frac{\sigma_b}{n_b}\right)$$

where $\sigma_s$ **is lowest tensile strength of the material at room temperature**

$\sigma_b$ **is lowest yield point of the material at room temperature;**

$\sigma_s^t$ **is lowest yield point of the material at design temperature;**

$n_s$ , $n_s^t$ , $n_b$ **are design factors of the material.**

**In JB4732《Steel Pressure Vessel——Code for Design by Analysis》**

$n_s = n_s^t \geq 1.5$ ,  $n_b \geq 2.6$

## Limit analysis and shakedown analysis:

**Limit analysis and shakedown analysis are used to set up the limits for stress intensities.**

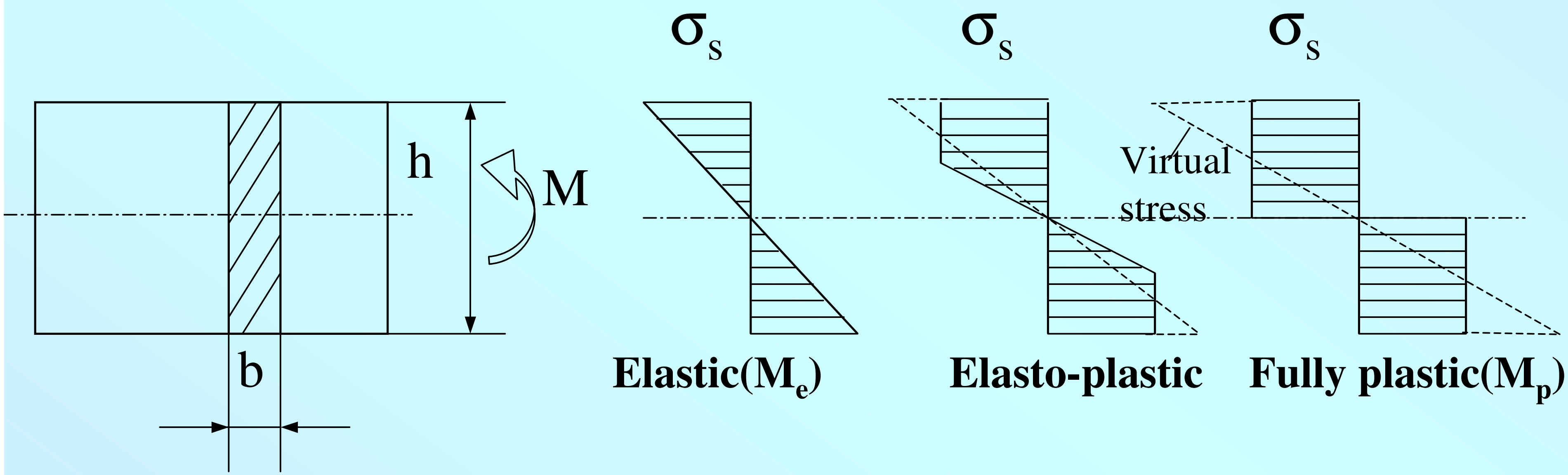



**图4-59 Limit analysis for a beam with bending action**

$$M_p = \sigma_s \frac{bh^2}{4}$$

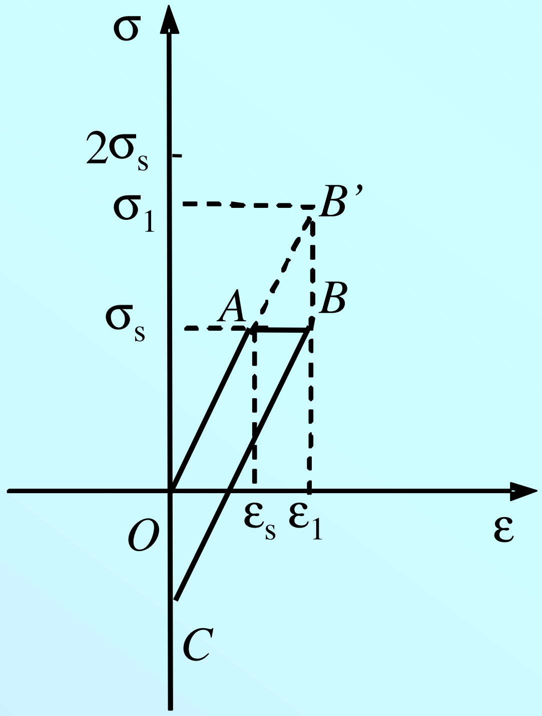
or

$$M_p = 1.5 M_e$$

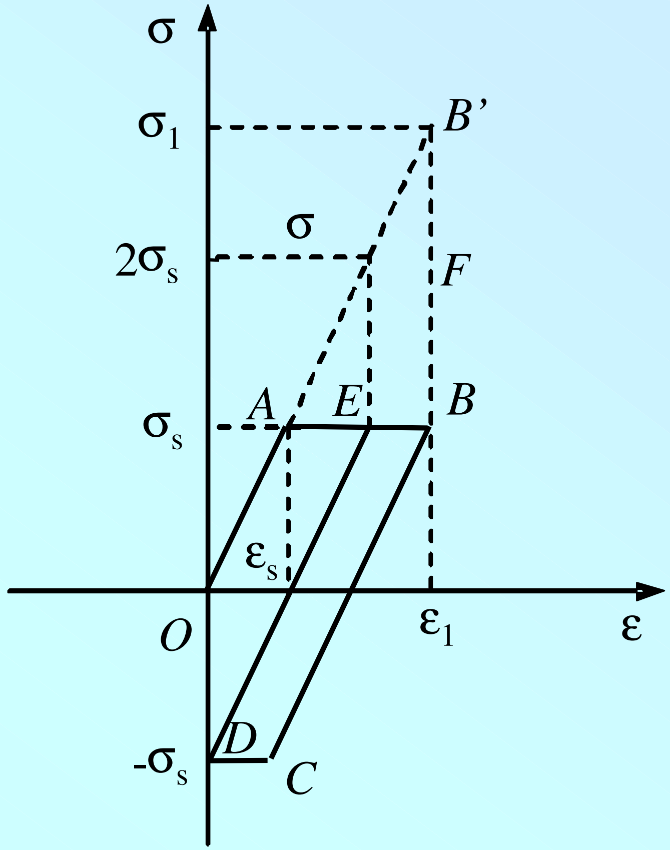
$$\sigma'_{\max} = \frac{6M_p}{bh^2} = 1.5\sigma_s$$

**So the limit for stress intensity calculated from** $P_b$ **is** $1.5S_m$ .

## （2）Shakedown analysis




(a)




(b)

**Fig. 4-60 Shakedown analysis**

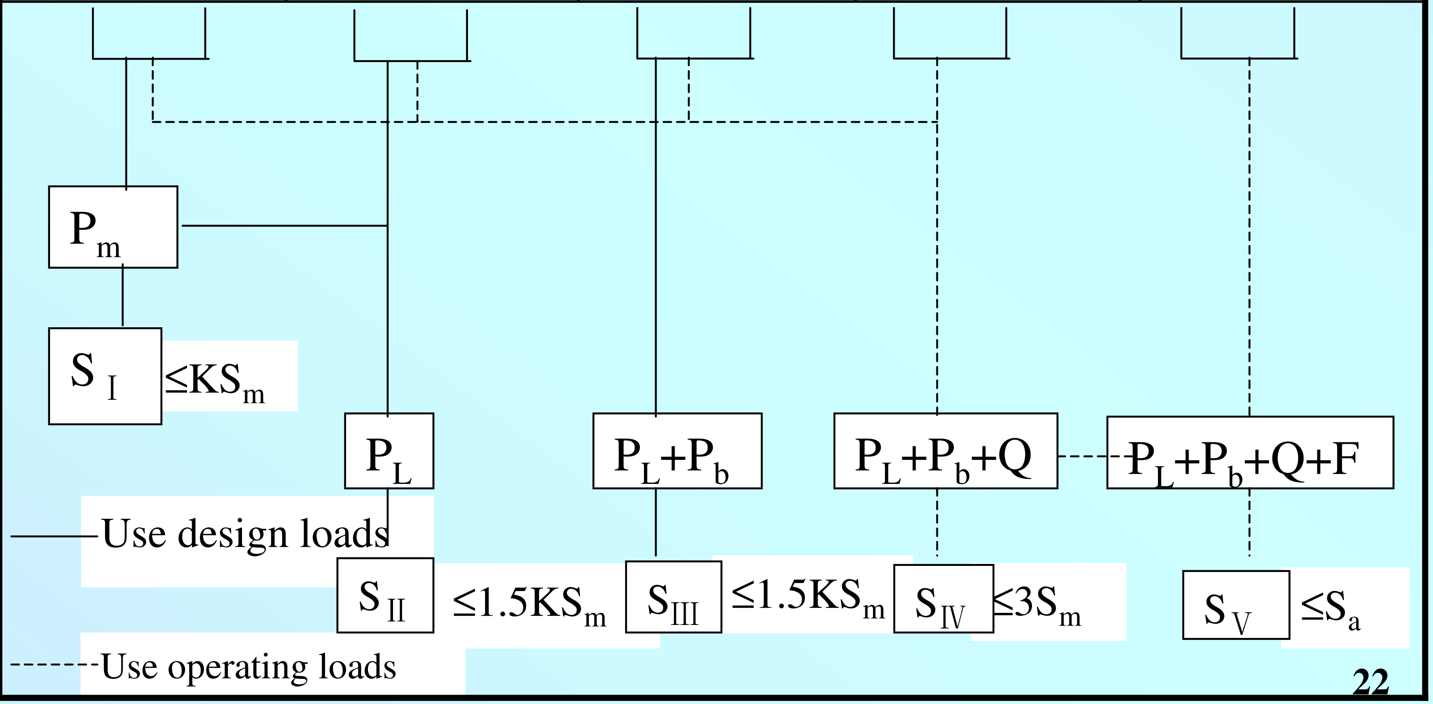
**The maximum stress range for shakedown is** $\sigma_1 \le 2\sigma_s$ ，

**as** $\sigma_s \ge 1.5S_m$ **, the limit for primary plus secondary stress is 3S$_m$ .**

# Limits of stress intensities

| Stress Category | Primary | | | Secondary Membrane plus Bending | Peak |
|---|---|---|---|---|---|
| | General Membrane | Local Membrane | Bending | | |
| Symbol | $P_m$ | $P_L$ | $P_b$ | Q | F |

Combination of stress components and allowable limits of stress intensities



# 4.4.5 Application of Design by Analysis

## Steps for pressure vessel design-by-analysis

(1) Design of Structure

(2) Mechanical modeling

(3) Stress analysis

(4) Stress category

(5) Calculation of stress intensities

(6) Check of stress intensities

## Application of the code for design-by-analysis

**The codes for design-by-rule and design-by-analysis are independent from each other. Either one can be used for pressure vessel design, but they cannot be composed together.**

**For the following cases, it is recommended to use the code for designing-by-analysis to design pressure.**

**(1) Vessels with high pressure and large diameter;**

**(2) Vessels under fatigue loading;**

**(3) Vessels with complicated structures.**