第3章　消能减震结构
Chapter 3 Seismic Energy-Dissipated Structure

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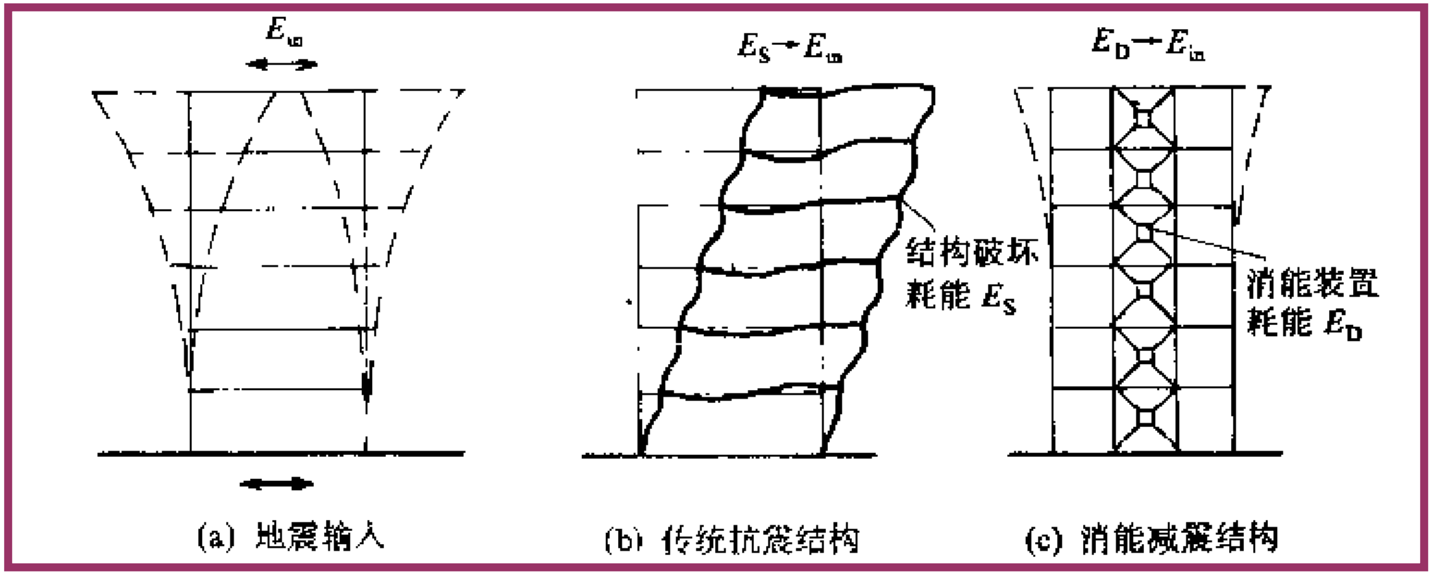
3.1 结构消能减震概述

Overview of Seismic energy-dissipated structure

3.1.1 结构消能减震的基本概念

Basic concept of energy dissipation



传统结构 Conventional structure

$$E_{in}=E_R+E_D+E_S \qquad (3.1.1)$$

消能减震结构 energy-dissipated structure

$$E_{in}=E_R+E_D+E_S+E_A \qquad (3.1.2)$$

E_{in}：地震输入的能量;

Input energy of earthquake

E_R：结构地震反应能量，包括动能和势能。

seismic response energy of structure including kinetic and potential energy

E_D：结构阻尼消耗的能量。

Energy dissipated by structural damping

E_S：结构构件或非结构构件非弹性变形消耗的能量

Energy dissipated by inelastic deformation of structural or non-structural elements

E_A：耗能装置消耗的能量

Energy dissipated by supplemental energy-dissipating device

E_D 结构阻尼耗能很小（5%）,要使 E_R 减小到零，即地震反终止，E_S 必然很大，即以结构破坏为代价。而减震结构是将地震能量由耗能装置消散。

Generally Energy dissipated by structural damping (E_D) is limited about 5 percent. To reduce E_R to zero, E_S must be large, that is, reducing the structural dynamic response have to pay the price of structural damage or destroy. While in energy-dissipated structures, earthquake energy was consumed by the energy-dissipating devices.

- **energy-dissipated structure**

  Besides the isolation structure, another approach to improved earthquake response performance and damage control is that of supplemental damping systems, which is called energy-dissipated structure system. In these systems, mechanical devices are incorporated in the frame of the structure and dissipate energy throughout the height of the structure. The means by which energy is dissipated is either yielding of mild steel, sliding friction, motion of a piston within a viscous fluid, orificing of fluid, or viscoelastic action in polymeric materials.

3.1.2 结构消能减震的优越性及应用范围

The advantages and application of energy – dissipated structures

- advantages

（1）安全性 :地震反应减小40-60%

Safety: earthquake response reduced by 40% to 60%

（2）经济性： 节约造价5-10%

economy: cost saved by 5% to 10%

（3）技术合理性 technical rationality

3.1.2 结构消能减震的优越性及应用范围

The advantages and application of energy-dissipation structures

- application

（1）高层建筑，超高层建筑；

High-rise building, super high-rise building

（2）高柔结构，高耸塔架；

High and flexible structure, High-rise tower

（3）柔性管道、管线（生命线工程）；

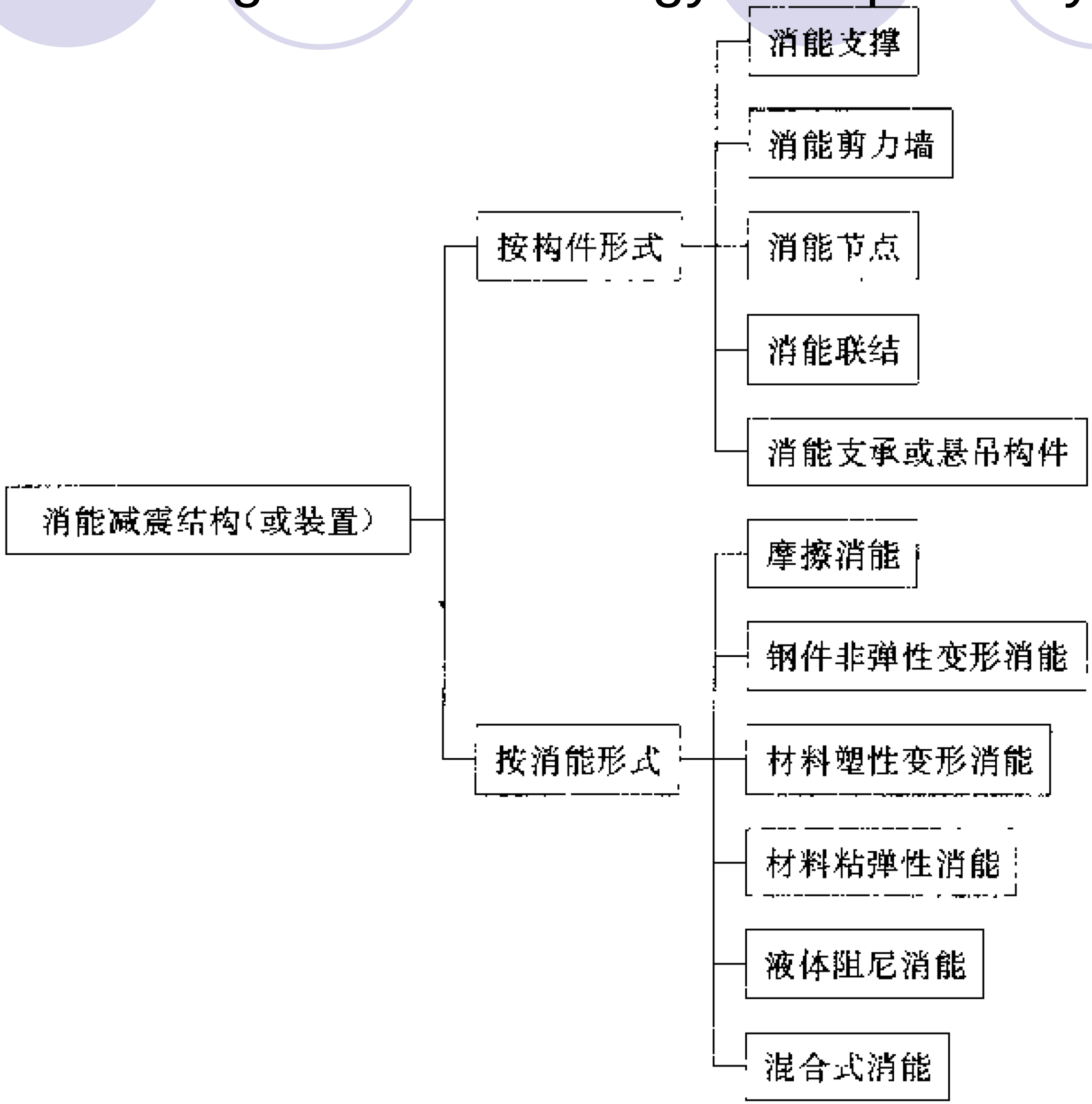
Flexible pipelines and wires (lifeline project)

（5）旧有高柔建筑或结构物的抗震（或抗风）性能的改善提高。

the improvement of seismic and wind-resisting ability of existed high and flexible buildings

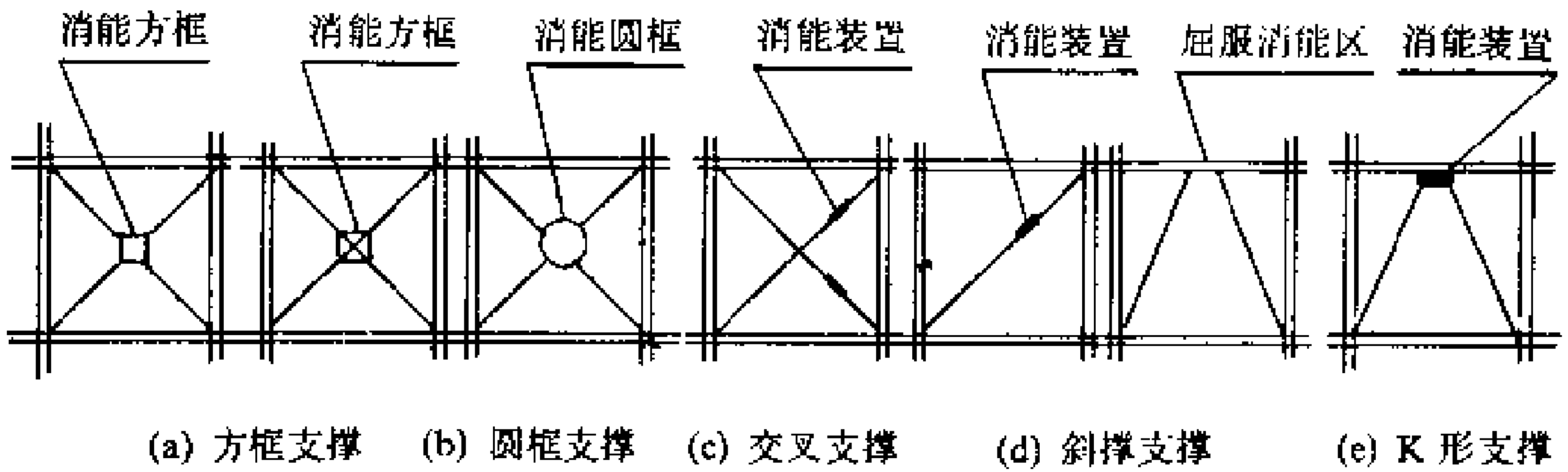
3.1.3 结构消能减震体系的分类和构造

Types and configuration of energy-Dissipated system



- 消能构件的不同构造形式
- Different types of energy-dissipating components

（1）消能支撑 energy-dissipating bracing



钢材受弯屈服型消能支撑
yielding steel bracing system

这种支撑体系，具有结构在一般使用情况下所要求的侧向刚度，能代替一般交叉支撑或剪力墙。又具有较高的减震消能能力和抗低周疲劳破坏的能力，在多次反复荷载作用下，不失稳，不断裂，保持稳定的承载力和消能能力。其荷载—位移滞回曲线包络图面积非常稳定和饱满，与交叉杆钢支撑相比，阻尼比增大5倍以上。

This type of bracing can replace ordinary cross-bracing or shear walls, has the required lateral stiffness under normal service. It also has high energy-dissipating and anti-fatigue destroy capacity; stability capacity, not fracturing and sustain a stable bearing capacity under multiple times of cyclic loads. Its load - displacement hysteretic loop is very stable and plump, whose damping ratio is 5 times as large as that of the cross-bar steel bracing

钢材受弯屈服型消能支撑

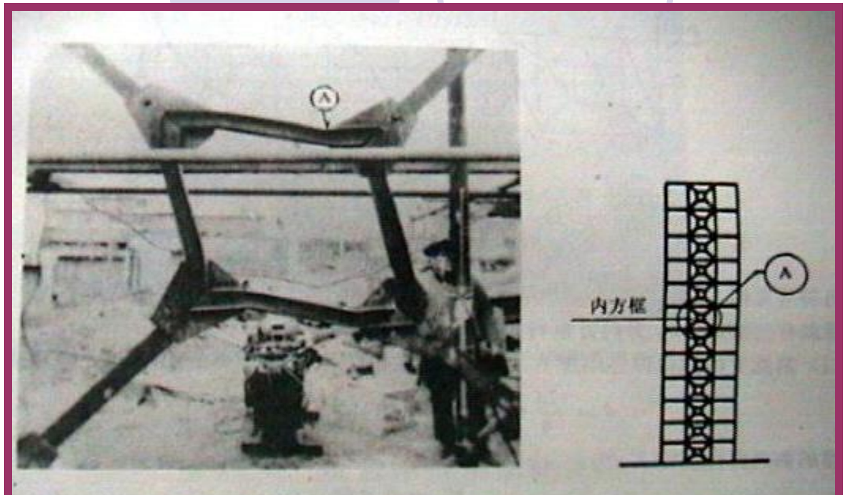
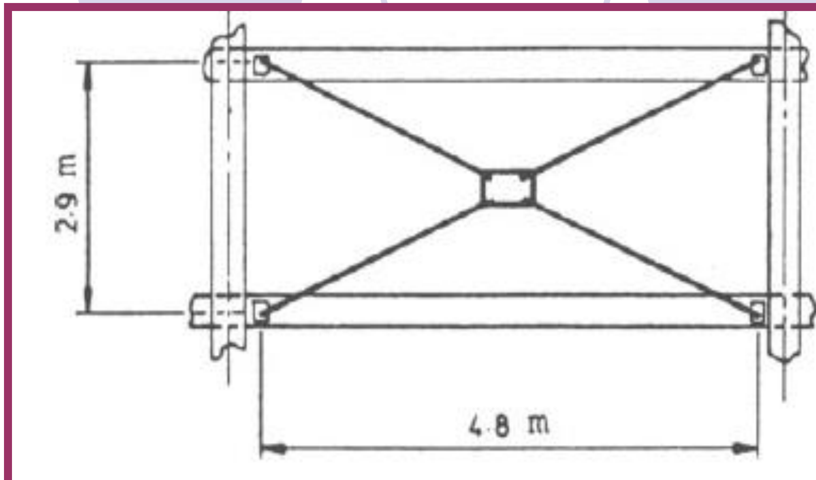


图 12-4-1　钢材受弯屈服型消能支撑减震结构体系



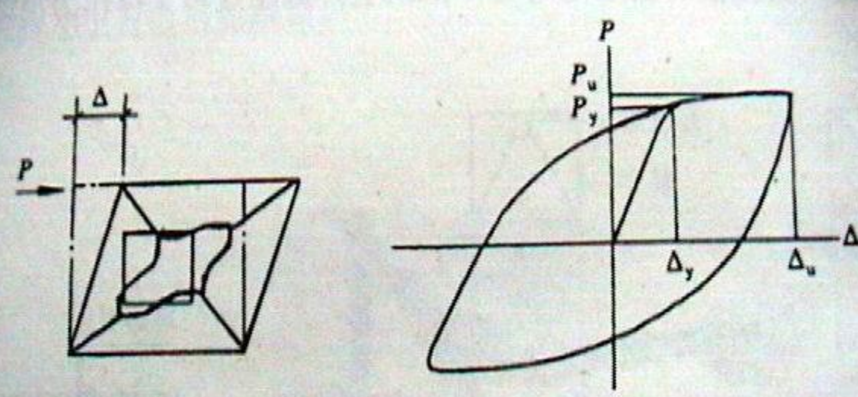
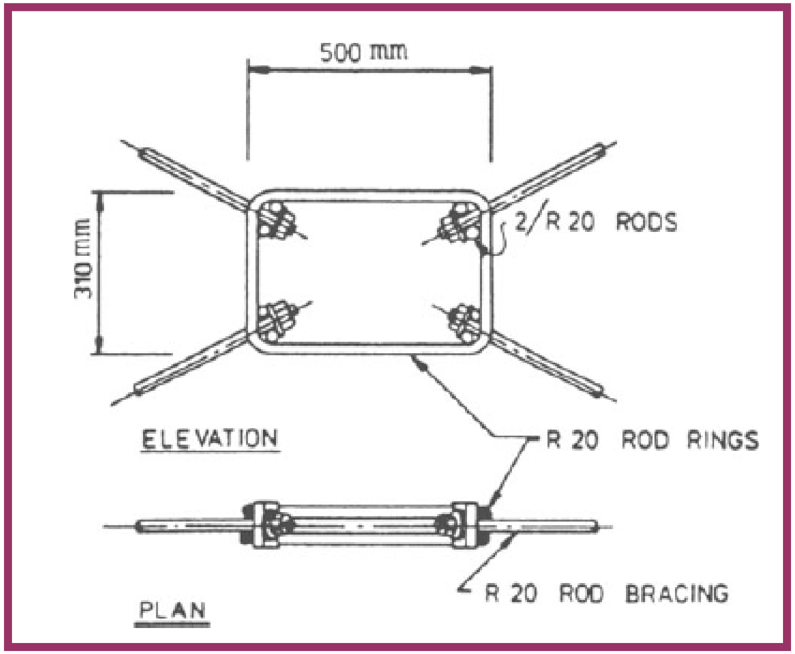
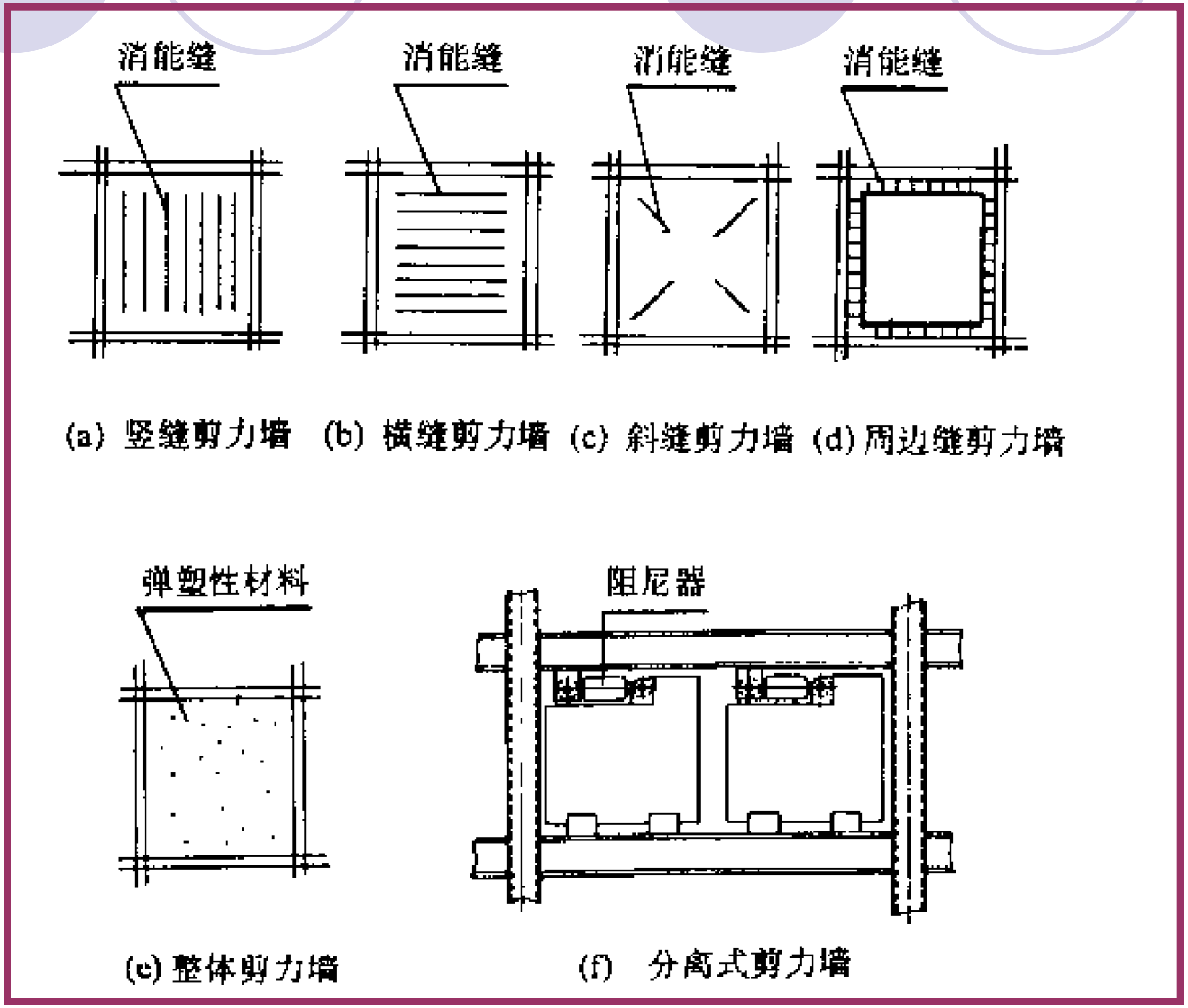


图 12-4-3　消能支撑荷载-变位滞回曲线

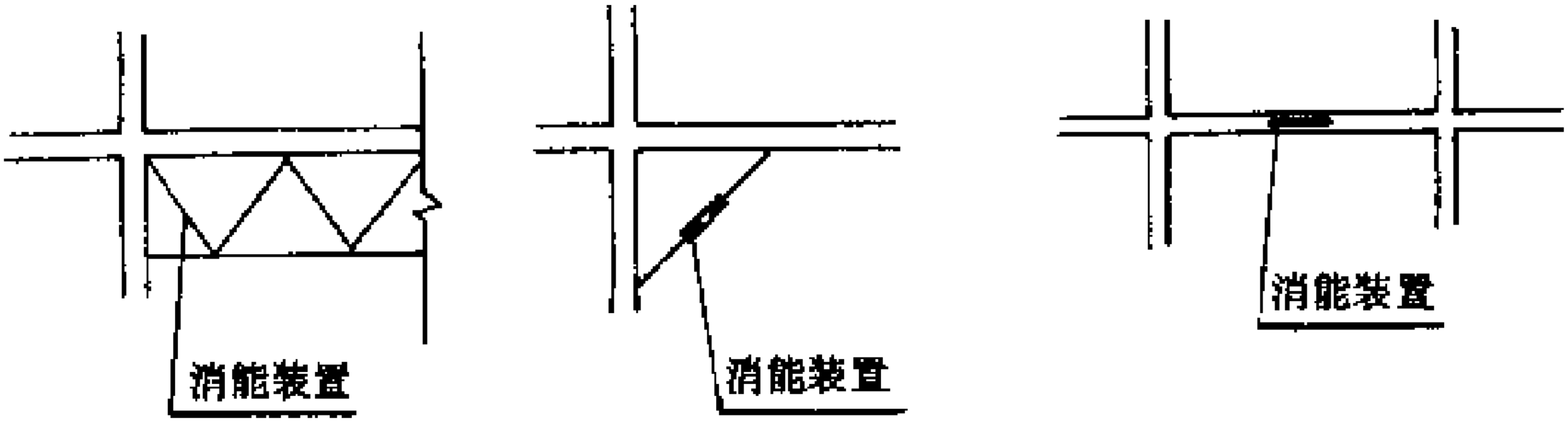
- An important characteristic of the element is that the compression brace disconnects from the rectangular steel frame so that buckling is prevented and pinched hysteretic behavior does not occur. Energy is dissipated by inelastic deformation of the rectangular steel frame in the diagonal direction of the tension brace.



（2）消能剪力墙 energy-dissipating shear wall

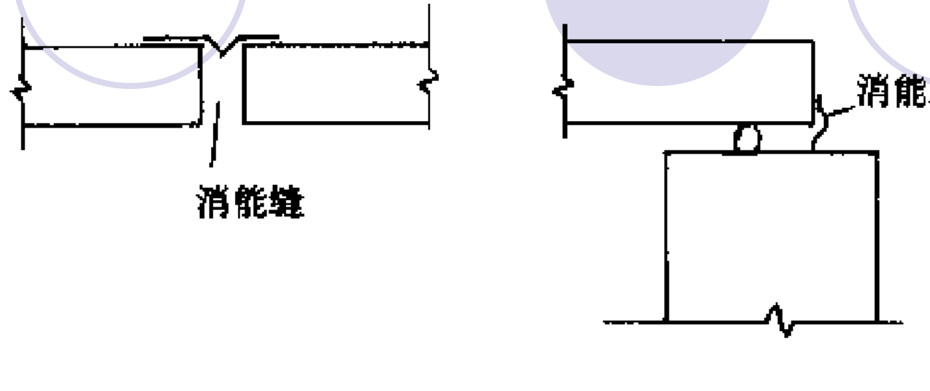


（3）消能节点 energy-dissipating node



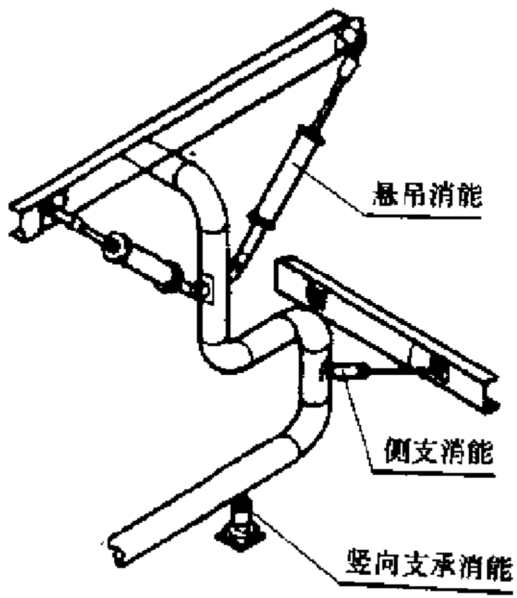
(a) 梁柱消能节点　　(b) 梁消能节点

（4）消能联结 energy-dissipating connection



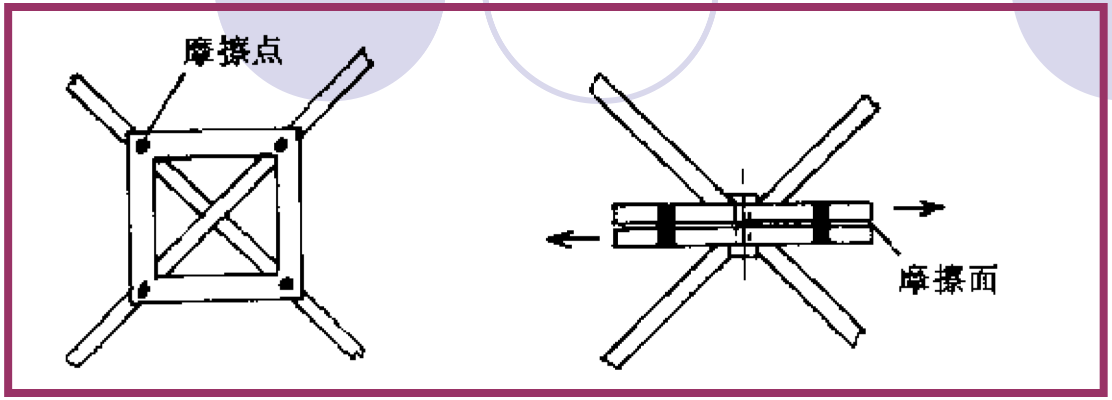
(a) 结构消能缝　(b) 结构消能联结

（5）消能支撑或悬吊构件 energy-dissipating supports and suspended members

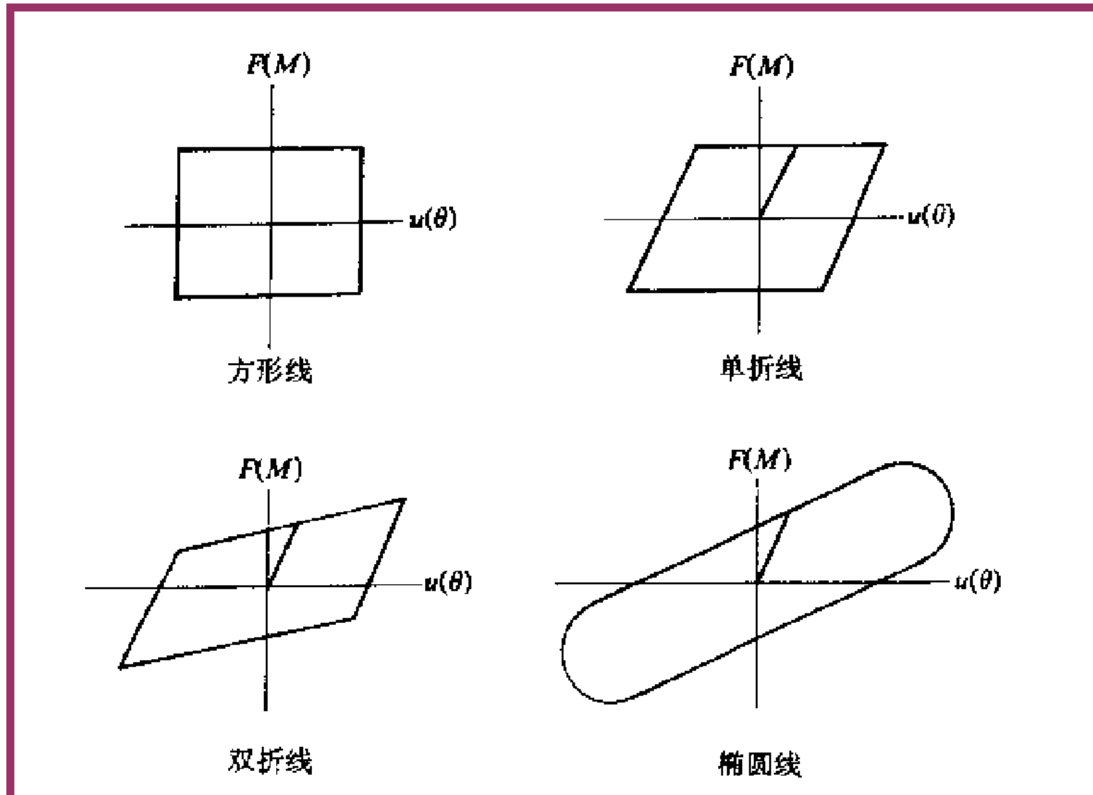


- 消能装置的不同消能形式
- Various energy-dissipating ways of devices
- 消能构件中设有消能装置。当构件（或节点）发生相对位移或转动时，消能装置产生较大的阻尼，从而发挥消能减震作用。为了达到最佳消能效果，要求消能装置提供最大的阻尼，即当构件（或节点）在力作用下发生位移时，所做的功最大。
- Energy-dissipating devices are mounted in energy-dissipating members. When the member (or node) produce relative displaces or rotates, the energy-dissipating devices produces large damping, which plays a role of energy dissipation. In order to achieve the best effect of energy dissipation, the energy-dissipating devices are required to provide maximum damping, that is, when the members (or nodes) displaced under force, the power is done to the most extent.

（1）摩擦消能：如摩擦消能支撑，摩擦节点



energy dissipated by friction : friction bracing, friction node



实例：Pall摩擦阻尼装置

Example: Pall friction damping device

Pall摩擦阻尼装置主要依靠材料接触面的滑动摩擦产生阻尼而对结构发挥消能减震作用的。摩擦力的大小通过材料摩擦面的摩擦系数和夹紧力来实现并进行调节。其早期典型摩擦阻尼机构如下图。

Pall friction damping devices mainly rely on sliding friction of material contact surface to produce damping in order to dissipate energy and reduce earthquake action. The magnitude of the friction was implemented and adjusted by the friction coefficient of the friction surface and the clamping force. Its early frictional damping mechanism is showed in the following figure.

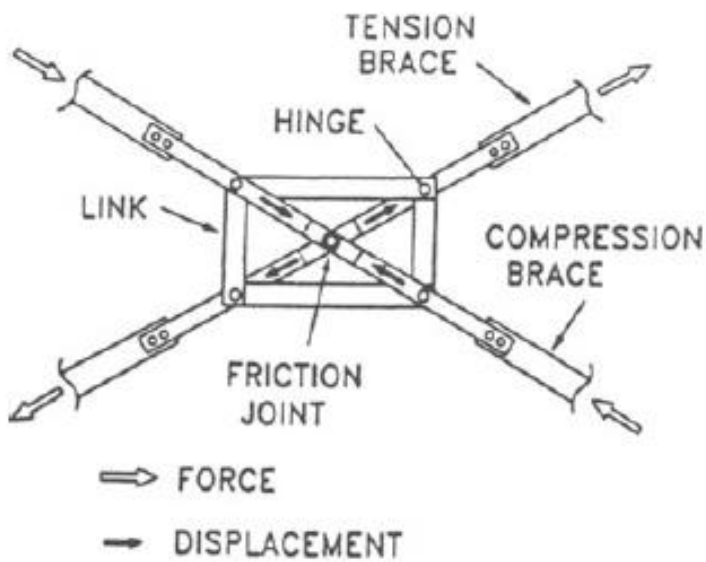
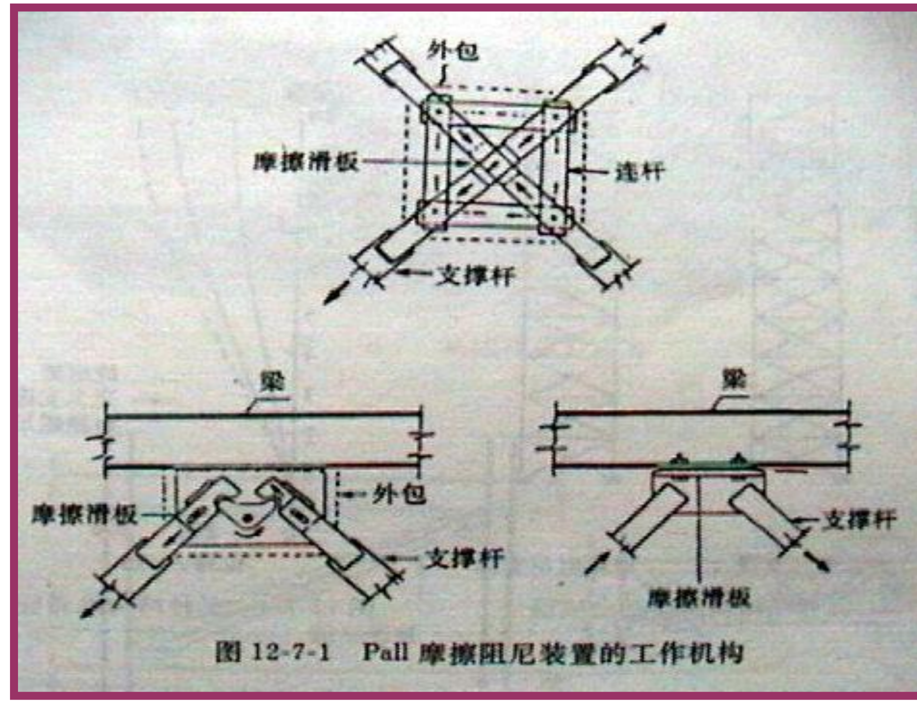


Figure 1 Friction Damper of Pall (1982).

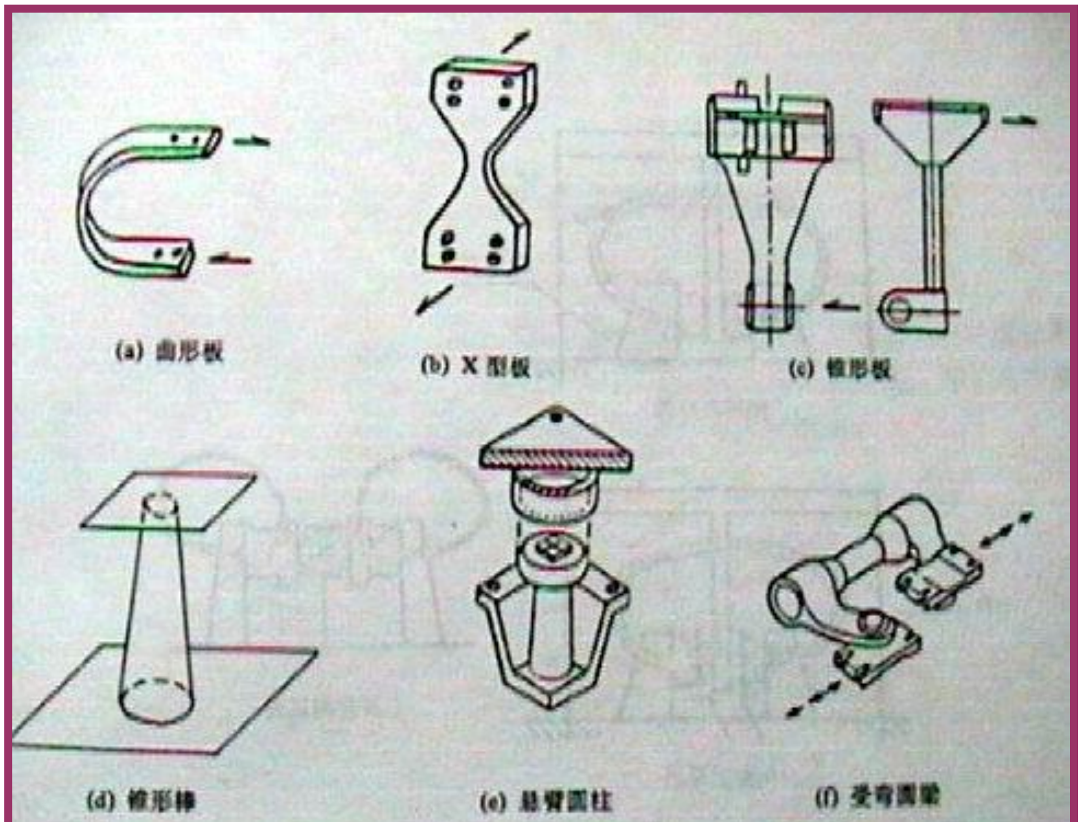


- Figure illustrates the design of this device. When seismic load is applied, the compression brace buckles while the tension brace induces slippage at the friction joint. This, in turn, activates the four links which force the compression brace to slip. In this manner, energy is dissipated in both braces while they are designed to be effective in tension only.
- Experimental studies confirmed that these friction devices could enhance the seismic performance of structures. The devices provided a substantial increase in energy dissipation capacity and reduced drifts in comparison to moment resisting frames.

（2）钢件（梁、板、棒）非弹性消能装置

- inelastic energy-dissipating steel devices (metallic damper)

- Various devices whose behavior is based on the yielding properties of mild steel, for example the Steel components (beams, plates and bars) shown in the following figures



环形钢板消能装置

软钢制作，具有较明显的屈服消能效果。环形钢板用软钢板条冷弯成环形形状，装设于结构的变形部位。当环形钢板发生较小水平位移时，钢板处于弹性工作状态，提供足够的刚度。当环形钢板发生较大水平位移时，部分材料进入非弹性状态并消耗地震能量，钢板被拉直，并限制结构的水平变位，从而对结构变形起“软锁”作用，这对消能减震结构是很有意义的。环形钢板在侧向和竖向变形时也能同样发挥弹性、消能和软锁的作用。

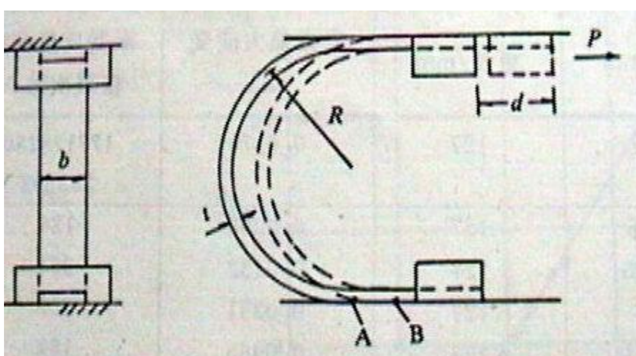


图 12-2-1 环形钢板消能元件

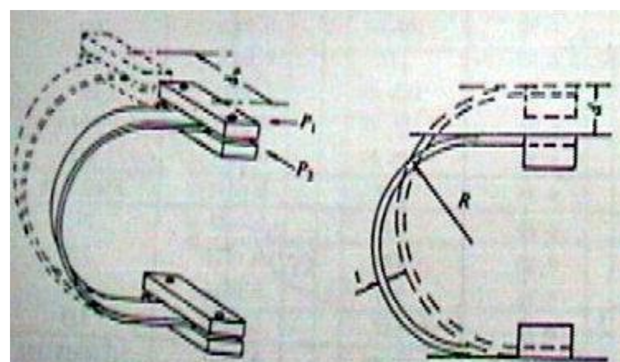


图 12-2-2 环形钢板侧向和竖向消能

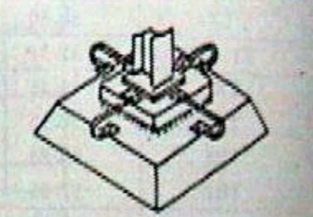


图 12-2-3 环形钢板多向布置

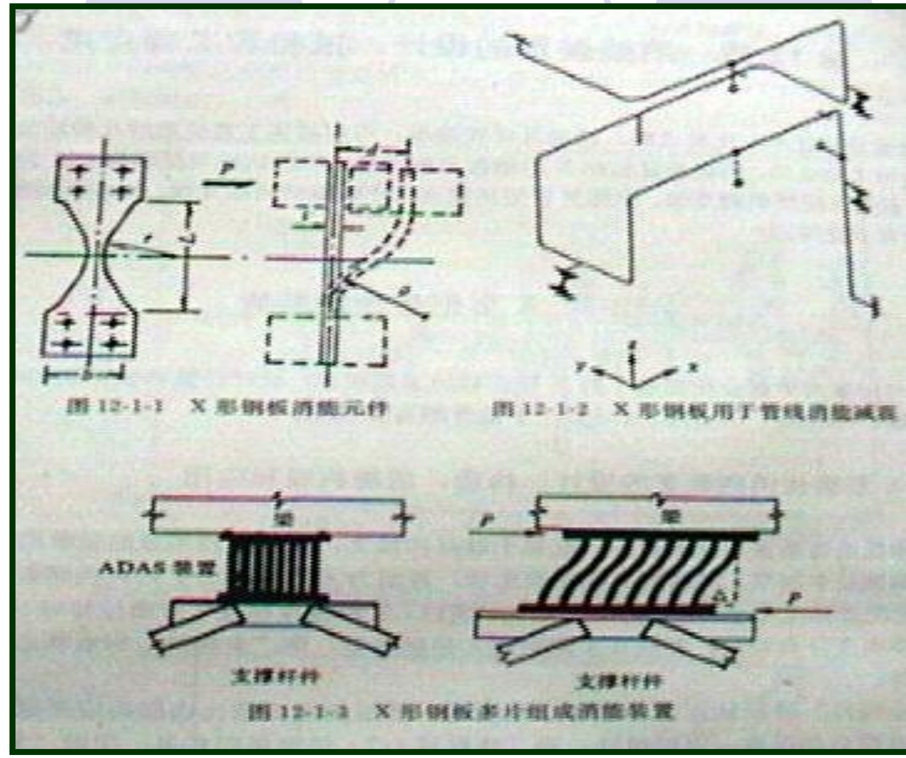
Annular steel plate energy-dissipating devices

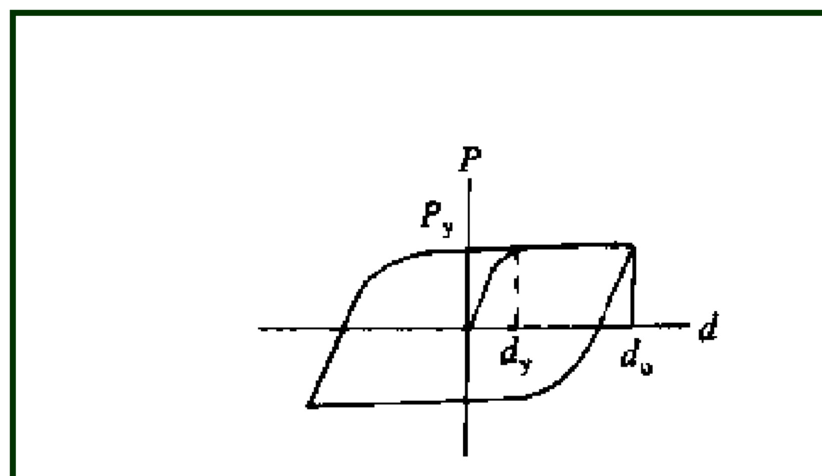
Annular steel plate energy-dissipating devices are made by mild steel which has obvious energy-dissipating effect after yielding. The steel plates are made by cold-forming mild steel into annular shape and fit into the deformed parts of the structure. When the annular plates produce small displacements, they works elastically, providing sufficient stiffness. When the annular plates produce large lateral displacements, part of the material enters plasticity and dissipates earthquake energy. And the plates was straightened, restraining structural horizontal displacement as “soft-lock”, which is meaningful to energy-dissipating structures. Moreover annular steel plates also can playing a role of elastic deformation, energy dissipating and soft locking when they produce lateral and vertical displacement,

X形钢板消能装置

软钢制作，X形钢板是中间窄、两端宽的变断面形状，近似为X形，当钢板发生弯曲位移时，弯曲应力和应变也是中间小、两端大。所以，在发生弯曲位移时，其钢材的应力和应变沿高度分布均匀，各点几乎同时进入屈服状态，即“全构件”屈服状态，发挥最大的消能效果。

在“全构件”屈服状态，在每个横断面，外层的应变值比内层的应变值大。在每个断面的中间部分保留一定的弹性，即“弹性核心”，使钢板仍具备一定的“复位”能力。



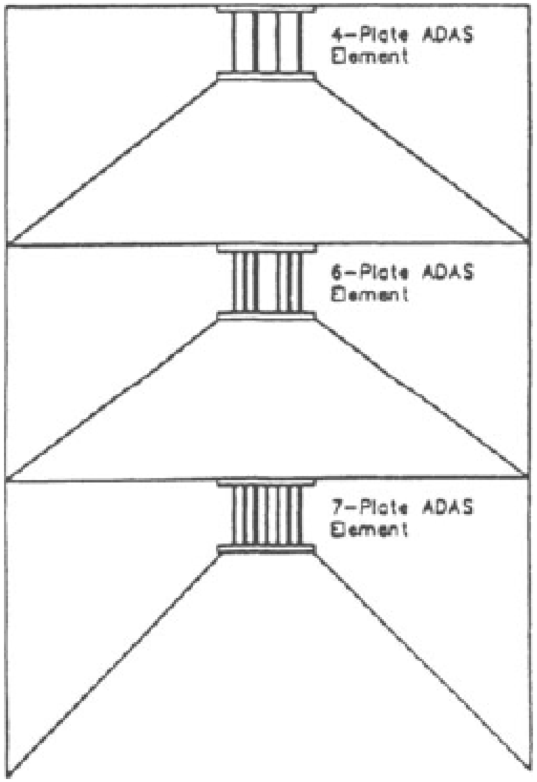


X形钢板消能装置 X-shape steel plate energy dissipating device (ADAS)

Made from mild steel, X-shape steel plate has a cross section which is narrow in the middle and broad in the two ends like an “X”. When the plate produces flexural displacement, the stresses in the steel plate distribute evenly over the height and yield over the entire length of the device, that is, global yield state, utilizing its energy dissipating capacity.

In the global yield state, the strain of the outer layer should be larger than that of the inner layer on every cross section. The center of every section should maintain some elasticity, namely, "elastic core", which provide the plate with a certain "reset" capability.

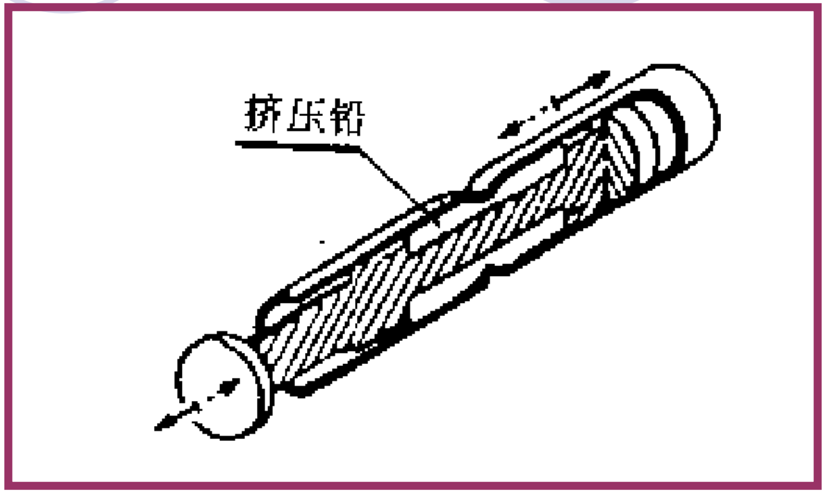
The device consists of multiple X-steel plates of the shape and installed as illustrated in the figure.



ADAS Element and Installation Detail (from Whittaker 1989).

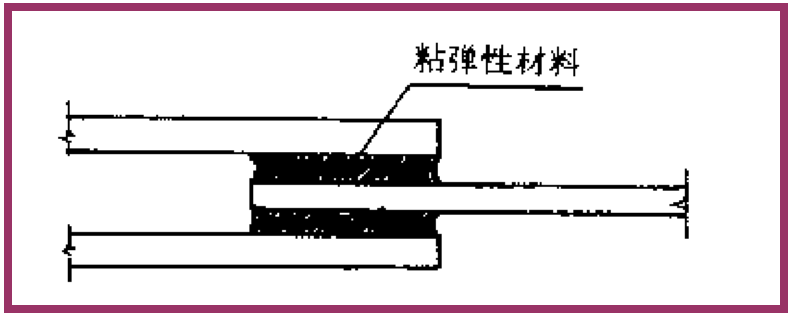
（3）材料塑性变形消能：如挤压铅阻尼器

Energy dissipated by plastic deformation of the material



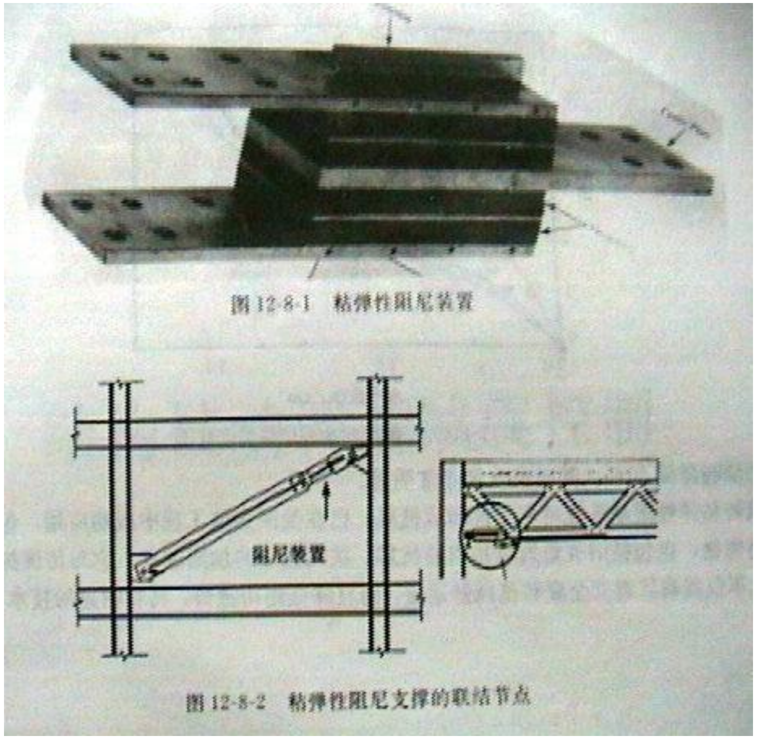
（4）材料粘弹性消能装置 viscoelastic damper

Energy dissipating device made by viscoelastic material



粘弹性阻尼装置实例

粘弹性阻尼装置主要由结构构件和粘结于结构构件之间的粘弹性材料组成。当结构构件产生相对位移时，粘弹性材料承受剪切应力和剪切变形，提供一定值的剪切弹性刚度和粘性阻尼。装设有粘弹性阻尼装置的建筑，一方面具有满足使用要求和结构复位要求的弹性刚度；一方面具有足够的阻尼值，以消耗地震能量，衰减结构地震反应。



粘弹性阻尼装置实例

Example of viscoelastic damping device

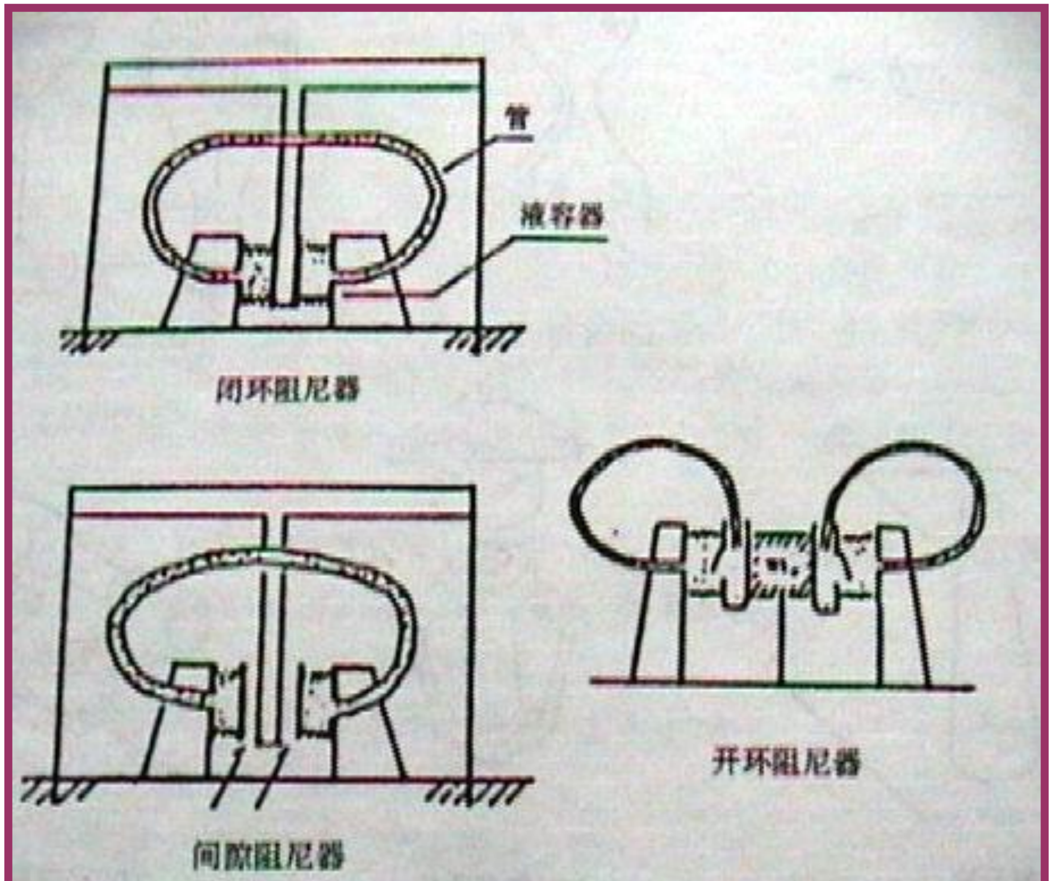
Viscoelastic damping device mainly consists of structural members and the viscoelastic material used to bond the members. When the structural members produce relative displacement, the viscoelastic material is subjected to shear stress and produces shear deformation, providing a certain level of shear elastic stiffness and viscous damping. On the one hand, buildings with viscoelastic damping devices has the elastic stiffness that is required for normal service and resetting of the structure, on the other hand, it also has sufficient damping to dissipate earthquake energy and reduce structural earthquake response

（5）液体阻尼消能：FLUID VISCOUS DAMPERS

energy dissipated by liquid: liquid damping pump

（6）混合式：几种消能形式混合应用

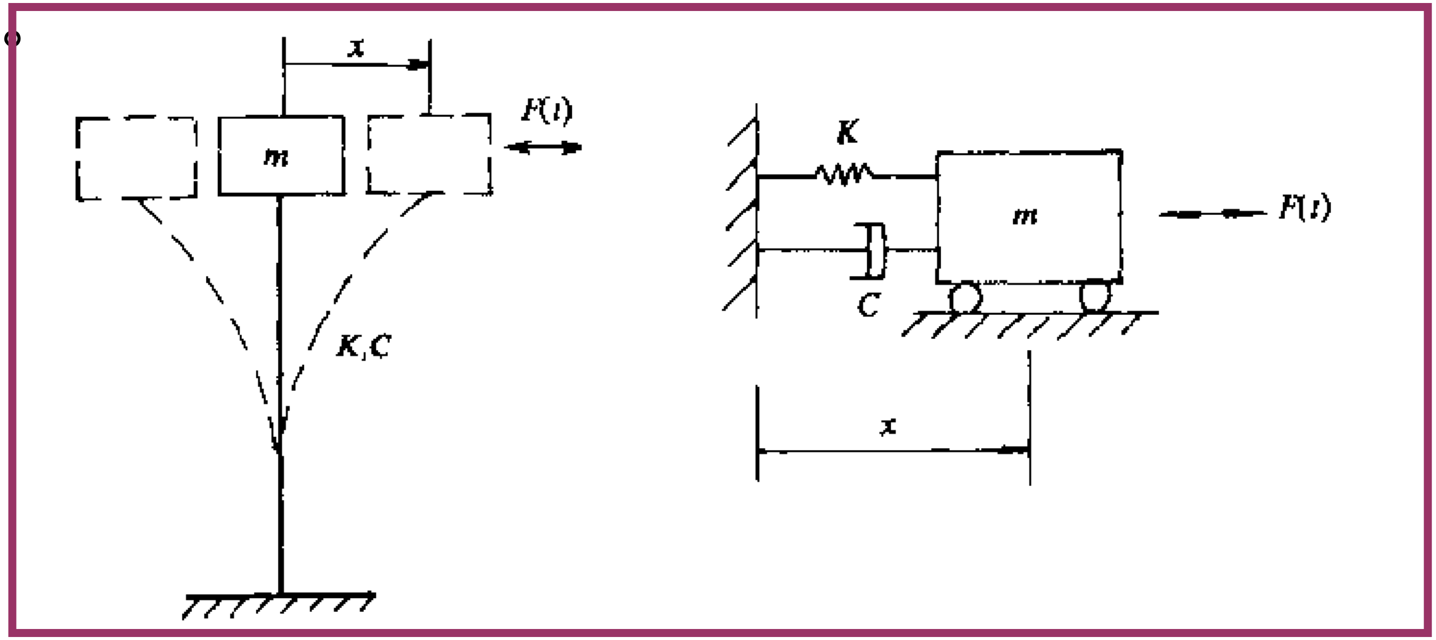
Hybrid: the hybrid of different energy dissipating method



3.2 结构消能减震机理

Mechanism of energy-dissipated structure

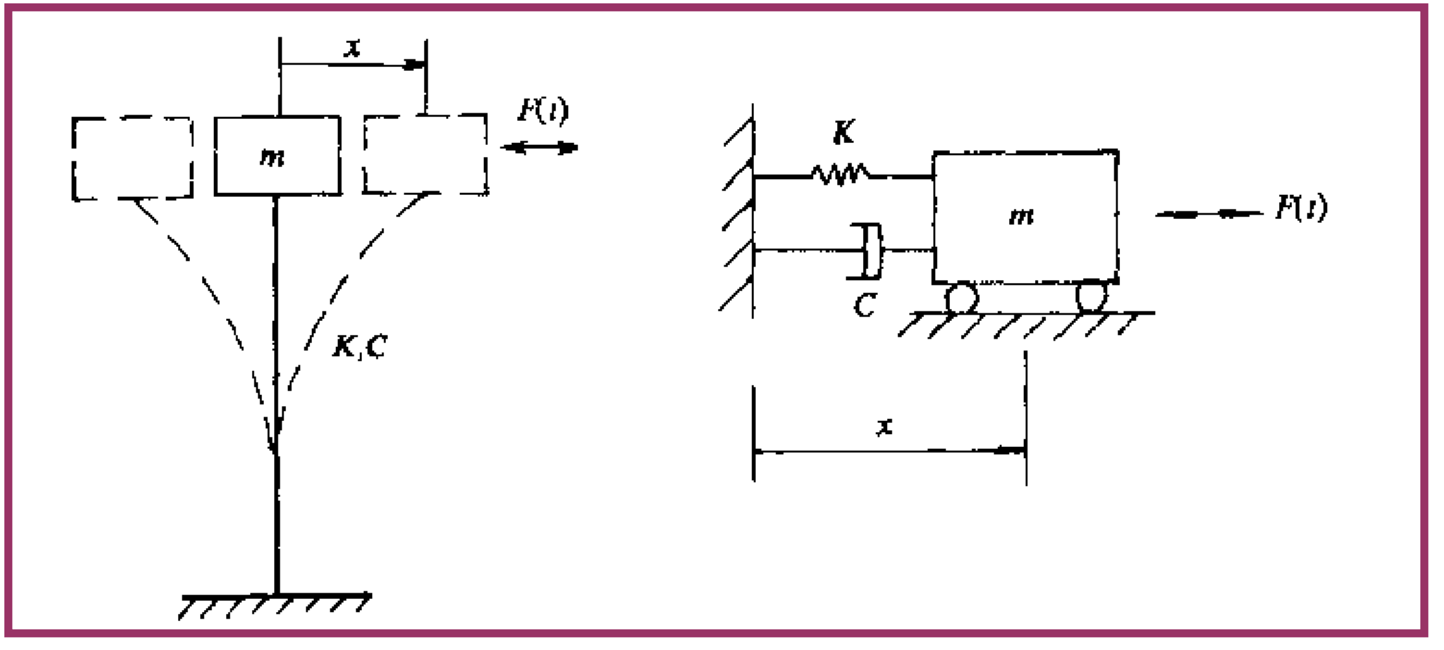
结构消能减震的实质是，在结构内设置消能构件（或消能装置），它们能为结构提供较大的阻尼，在地震时大量消耗输入结构的振动能量，衰减结构的地震反应。



3.2 结构消能减震机理

Mechanism of energy-dissipated structure

The essence of energy-dissipated structure is to install energy-dissipating components (or devices) in the structure, which can provide the structure with large damping, dissipating input energy under earthquake and reducing structural earthquake response.



3.2.1 结构体系自由振动消能减震

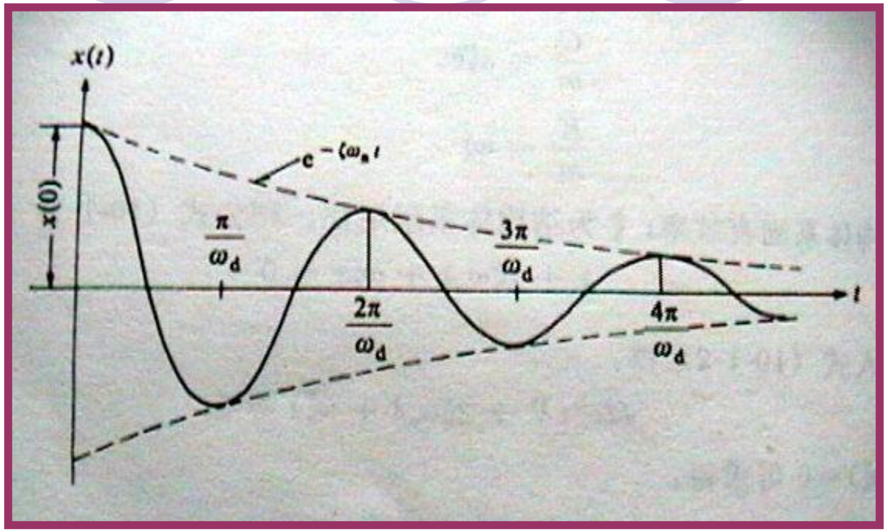
Energy dissipation in free vibration of structure

$$m\ddot{x}+C\dot{x}+Kx=0$$

$$\ddot{x}+2\zeta\omega_n\dot{x}+\omega_n{}^2x=0$$

$$x=e^{-\zeta\omega_n t}(A\cos\omega_d t+B\sin\omega_d t)$$

$$R=\sqrt{A^2+B^2}$$



令 $R=\sqrt{x_0{}^2+(\frac{\dot{x}_0+\zeta\omega_n x_0}{\omega_d})}$ 为合成矢量(composed vector)

$\Phi=\tan^{-1}\frac{(\dot{x}_0+\zeta\omega_n x_0)/\omega_d}{x_0}$ 为相位角(phase)

$$x(t)=e^{-\zeta\omega_n t}R\cos(\omega_d t-\Phi)$$

3.2.2消能减震结构体系的强迫振动

Forced vibration of Energy-dissipating structure

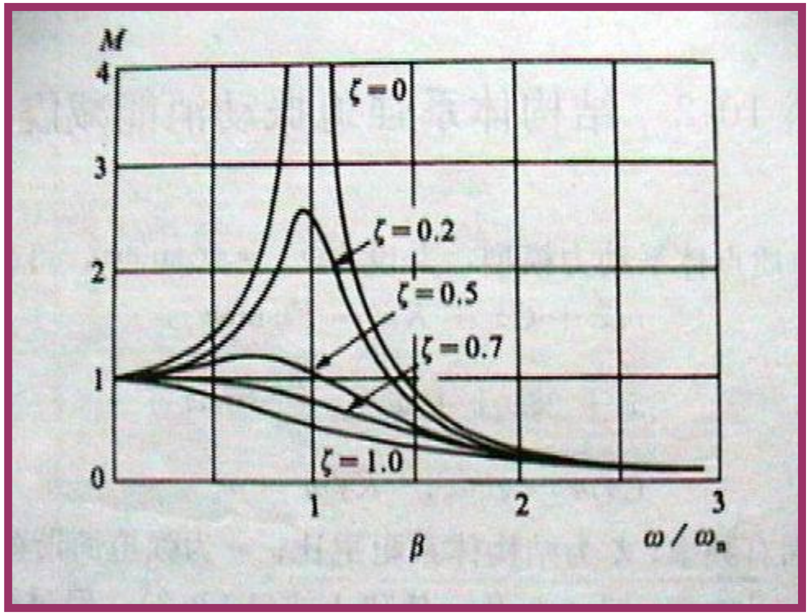
$$m\ddot{x}+C\dot{x}+Kx=F_0\sin\omega t$$

$$\ddot{x}+2\zeta\omega_n\dot{x}+\omega_n{}^2=\frac{F_0}{m}\sin\omega t$$

$$\Phi=\arctan\frac{2\zeta\omega/\omega_n}{1-(\omega/\omega_n)^2}$$

$$x=(F_0/K)\cdot M\sin(\omega t-\Phi)$$

$$M=\frac{1}{\sqrt{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}}$$



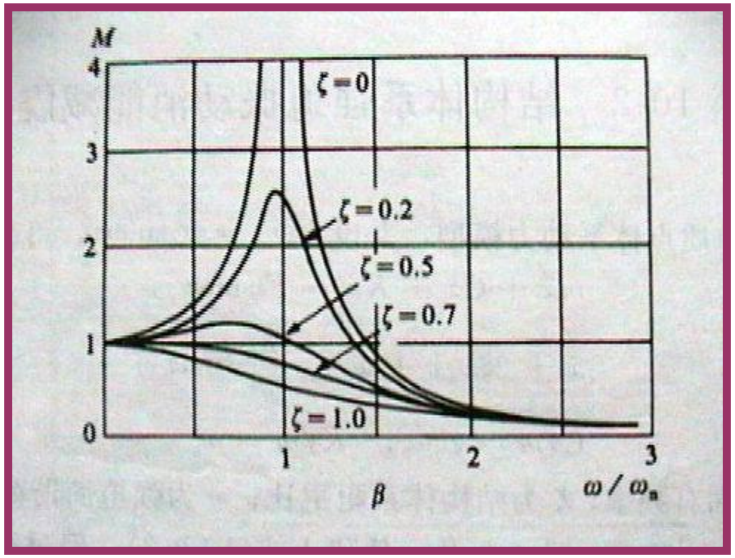
M为结构动力作用放大系数。即质点的振动反应x等于静力反应(F_0/K)乘以结构动力作用放大系数M。M值是决定结构体系振动反应的关键函数。如果M>1，则结构强迫振动为“放大”效应。M<1，则结构强迫振动为“衰减”效应，其分界线为M=1。

M is the amplification factor of structural dynamic action. The dynamic response of the mass equals the product of static response(F_0/K) and M. M is the crucial function that determines the dynamic response of the structure.

If M>1, the structural response is magnified.

If M<1, the structural response is reduced.

M=1 is the boundary point.



3.2.2 结构体系强迫振动消能减震

M：结构动力作用放大系数

（1）在（ω/ω_n）≤1.5的范围内，若结构体系阻尼ζ越小，则M值越大，结构振动为“放大”效应。若结构体系阻尼比ζ越大，则M值越小，结构振动为“衰减”效应。所以，在结构体系中设置消能构件（或消能装置），提供较大的阻尼，能有效地衰减结构的振动反应。

In the range of (ω/ω_n) ≤1.5, the smaller is the damping ζ of the structure, the larger is the value of M, and the structural vibration is magnified. If the large is the damping ζ of the structure, the smaller the value of M, then the structural vibration is attenuated. Therefore, Installation of the energy dissipating components (or devices) in the structure provides large damping which can effectively attenuate vibration response of structure.

3.2.2 结构体系强迫振动消能减震

M：结构动力作用放大系数

（2）当结构体系阻尼比ζ≥0.7时，在（ω/ω_n）的所有数值范围内，"结构动力作用放大系数"M永远小于1。这意味着，若在结构体系中装设消能构件（或装置），使其阻尼比达到一定数值，则在任何外力（地震、风等）冲击下，都能确保有效地衰减结构的振动反应。

When the damping ratio ζ of the structure is no less than 0.7, in the all possible range of (ω/ω_n), the structural dynamic amplification factor M is always lesser than 1. It means that if energy-dissipating components (devices) are disposed in the structural system, making the damping ratio reaches a certain level, then the structure can retain an attenuated vibrating response under the impact of any external load (earthquake, wind, etc.)

3.3　结构消能减震体系设计

Design of structural energy dissipating system

3.3.1 耗能减震结构的设计要求

Design requirements of energy dissipating structure

- 耗能构件的设置 The disposition of energy dissipating members

根据罕遇地震下的预期结构位移控制要求，设置适当的耗能部件

Install energy dissipating devices properly according to the requirement of predicted displacement of structure under the rare earthquake

耗能部件应沿结构两个主轴方向分别设置，宜设置在层间变形较大的位置，数量和分布由综合分析确定。

Energy dissipating components should be set along the two main axis and where the interstory drift is large. Its number and disposition are determined after comprehensive analysis.

- 耗能构件的性能要求
- The performance requirement of energy dissipating devices
  - 具有足够的吸收和耗散地震能量的能力和适当的阻尼
    - Sufficient energy absorbing and dissipating capacity and proper damping
  - 具有足够的初始刚度
    - considerable initial stiffness
  - 具有优良的耐久性
    - Good durability
  - 构造简单，宜施工，宜维修
    - Simple configuration. easy construction and maintenance

3.3.2 耗能减震结构的抗震计算

Seismic Design of energy dissipated structures

结构消能减震体系三种实用设计计算方法：

Three practical design methods:

循环设计法 (cyclic design method)

时程分析法 (time-history analysis)

能量分析法 (energy analysis method)

- 循环设计法 Cyclic Design
- 根据设计目标进行循环多次的设计计算，不断调整消能构件（或消能装置）的设计和布置，直到满足设计要求而完成设计的方法，称“循环设计法”。
  - Design and calculate for multiple times according to the design objective, and adjust the design and layout of energy dissipating components (devices) until they satisfy the design requirement. This design method is called cyclic design

- 基本假定 Assumptions

（1）装设有消能构件（或消能装置）的结构，在设定的强地震中处于弹性状态。

Structures with energy dissipating components (or devices) work elasticialy in the earthquake.

（2）消能构件（或消能装置）的刚度(k_a)和阻尼比（ζ_a）必须通过消能构件（或消能装置）的足尺试验测定。

The stiffness k_a and damping ratio of energy dissipating components (or devices) ζ_a must be decided through their full-scale test.

（3）消能减震结构的层间刚度(k)等于主体结构的层间弹性刚度（k_s）与实际布置在该层的消能构件（或消能装置）在相应层间位移状态下的刚度(k_a)之和。

The total story stiffness (k) of energy dissipated structure shall be the total sum of structural stiffness (k_s) and the effective stiffness (k_a) of energy dissipating components (or devices) that actually installed at the story under the corresponding story drift.

基本假定 Assumptions

（4）消能减震结构的等效阻尼比（ ζ ）等于消能构件（或消能装置）在相应层间位移状态下的阻尼比(ζ_a)， $\zeta_i=\zeta_{ai}$。

the equivalent damping ratio of energy dissipated structures (ζ) is the damping ratio of energy-dissipating components under the corresponding story drift (ζ_a), that is $\zeta_i=\zeta_{ai}$.

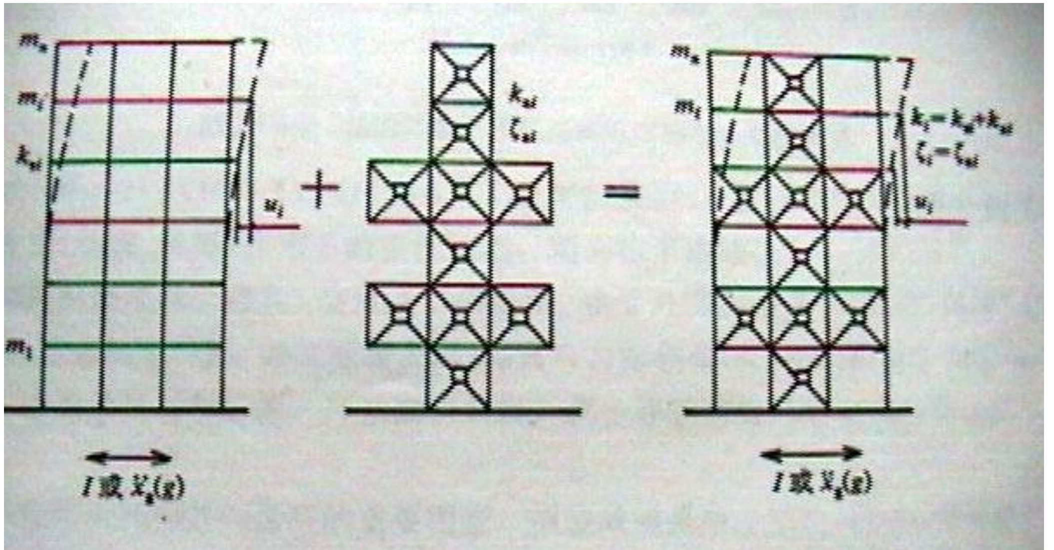


图 11-1-1 高层建筑消能减震结构体系

设计步骤 Design procedures

（1）确定结构减震目标

Determine the seismic mitigation objective of the structure

（2）主体结构设计

Design the main structure

（3）结构弹性动力分析

Structural elastic dynamic analysis

（4）确定结构所需的阻尼比[ζ_i]

Determine the required damping ratio of the structure [ζ_i]

（5）选择及布置消能构件（或消能装置）

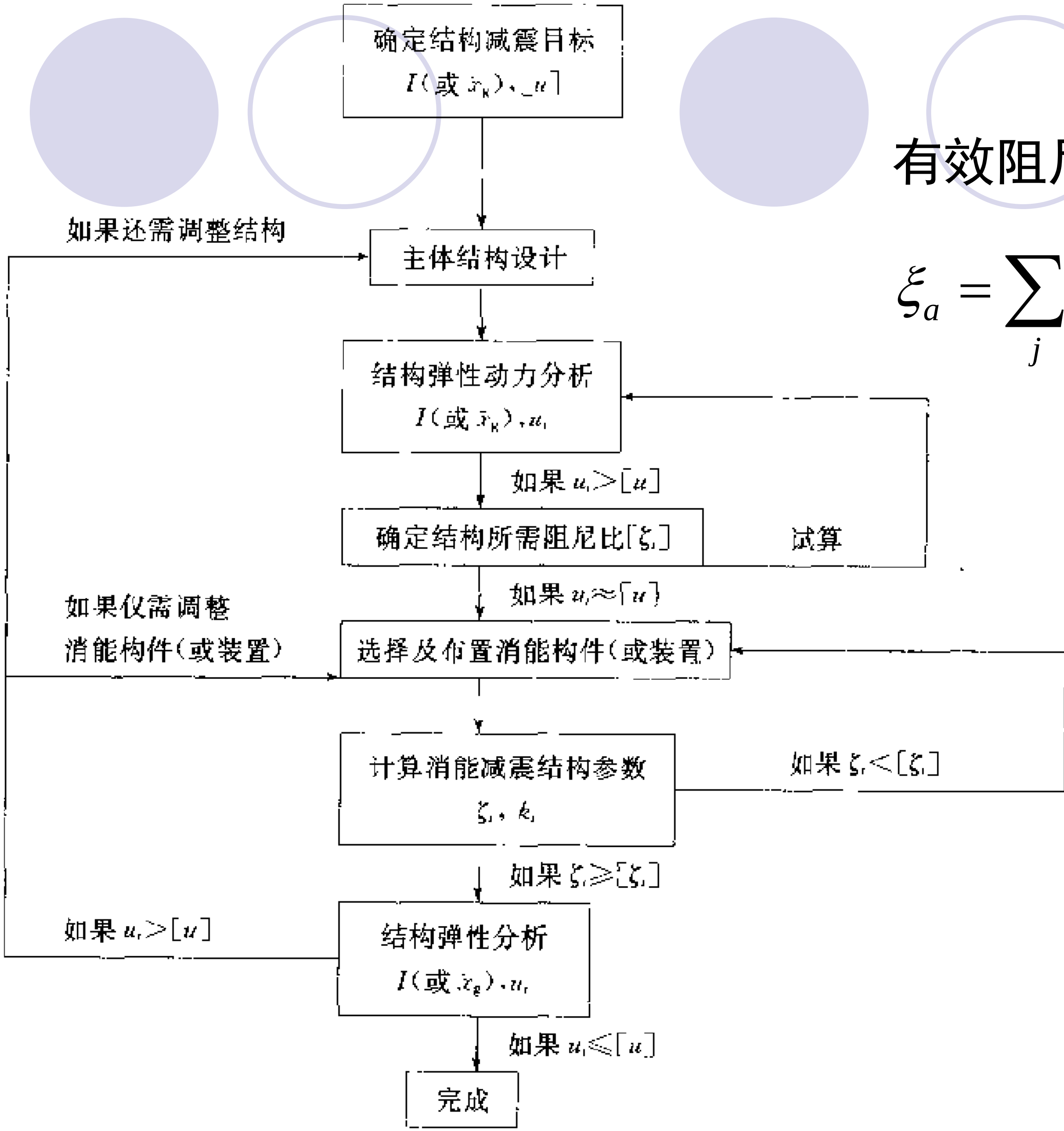
Selection and layout of energy-dissipating components.

（6）计算消能减震结构体系的动力参数

Calculate the dynamic parameter of the energy-dissipated structures

（7）消能减震结构体系的结构弹性分析

the elastic analysis of energy-dissipated structure



有效阻尼比的计算：

$$\xi_a = \sum_j W_{cj} /(4\pi W_s)$$

应用范围和评价 Applications and assessments

Cyclic design method can be used in

（1）任何高层建筑、高柔建筑、大跨度结构、大跨度桥梁等消能减震结构体系

Any high-rise building, high-flexible building, large span structure, large span bridge or other energy dissipated structures.

（2）任何地震烈度或地震波输入

Any level of Seismic intensity or any inputted seismic wave

（3）各种类型和消能构件（消能支撑、消能剪力墙、消能联结节点等）或消能装置

Any kinds of energy dissipating components including supports, shear walls, connection joint nodes and energy-dissipating devices

对该方法的评价(assessments):

（1）应用已有的较为成熟的弹性结构动力分析程序，现实可行，设计计算结果可靠

It can adopt the mature elastic structural dynamic analysis program, the design is reliable

（2）可达到较高的精确度

It can achieve high accuracy

（3）需多次循环设计，设计计算工作量稍大，周期稍长

multiple times of cyclic design are required , the design work is arduous and time-consuming.

时程分析法 Time history analysis

采用时程分析法对高层建筑消能减震结构体系进行分析时，体系的刚度和阻尼是时间的函数，随着消能构件（或消能装置）处于不同的工作状态而变化。

In the time history analysis of high-rise building structure with energy dissipating system, stiffness and damping of the structure is a function of time, which changes with the working states of the energy dissipating components (or devices).

消能减震结构体系的动力微分方程为：

The dynamic equation of energy dissipated system

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{I\}\ddot{x}_g(t)$$

- 时程分析法
  - 消能减震结构体系的设计原则是，主体结构在强地震中仍处于弹性状态，所以，体系的非线性特性是由消能构件（或消能装置）的非线性工作状态产生的。这样，体系的刚度矩阵[K]包括线性部分（主体结构）和非线性部分（消能构件或装置），体系的阻尼矩阵[C]忽略主体结构的阻尼影响, 考虑非线性部分（消能构件或装置）。
  - The design principle of energy dissipated structure is that the main structure works in elastic stage under strong earthquake. So, the non-linearity of the structure is induced by the non-linear state of energy dissipating components (or devices) . The stiffness matrix [K] of the system includes linear part (main structure) and non-linear part (energy dissipating components or devices). With non-linear part (energy dissipating members or devices) taken into consideration, the effects of damping of the main structure in the calculation of the damping matrix is neglected.

能量平衡法 Energy balancing method

根据能量平衡的原则，能量平衡方程

Based on energy balance, the energy balancing equation is

$$E_{in}=E_P+E_K+E_D+E_A$$

式中 E_{in}—地震输入时结构体系的能量；

input Energy by earthquake

E_P— 结构体系振动的势能；

Vibration potential energy of the structural system

E_K—结构体系振动的动能；

Vibration kinetic energy of the structural system

E_D—结构体系的结构阻尼消耗的能量；

energy dissipated by the damping of the structural system

E_A—消能构件（或消能装置）消耗的能量。

Energy dissipated by energy dissipating members

- 能量平衡法 Energy balancing method

对于消能减震结构体系，为了确保主体结构在地震中的安全，其消能构件（消能装置）必须有足够的消能能力，即必须满足下式要求：

For energy dissipating systems, in order to ensure the safety of the main structure under earthquake, the energy dissipating components (or devices) must have sufficient energy dissipating capacity, which means following requirements must be meet with

$$E_A \geq E_{in} - E_P - E_K - E_D$$