Application of Vibration Control

Masato Ohata

Advanced Structural Engineering Department, Takenaka Corporation
Tokyo, JAPAN

Feb. 2021

Contents

1. The summary of today's lecture

Summary

A vibration control structure uses mechanical equipment provided in the building to absorb building shaking that is produced by earthquakes and wind. There are two main types of vibration control（hereinafter VC): passive VC and active VC.

Passive VC exerts a damping effect even when no energy from a power source or the like is provided. Passive damping includes the Tuned Mass Damper (TMD) that uses a weight that sways with the same period as the building, and added dampers in which a damper is used to connect two points at which displacement is produced when the building vibrates.

Active VC uses a computer-controlled actuator operated by hydraulic pressure, electricity or the like to achieve higher damping effectiveness. Active damping includes the Active Mass Damper (AMD), in which a weight is moved by an actuator, allowing its reaction force to prevent the building from swaying, and the Active Brace System (ABS) that controls the axial force of braces and the like.

Today, I will mainly focus on the passive VC, from the flow of the structure plan, there is what kind of VC system, and explain election for method in the design, layout planning, also the considerations on the analysis. In addition, and I will explain the inspection of the method used to introduce the VC devices and maintenance.

2. The types of dampers

The types of damper

These dampers use the elasto-plastic hysteresis energy characteristics. Many of them use the capacity of the steel to absorb plastic strain energy. Steel with an ultra-low yield point has been developed, and lead, tin and other materials are also used. These are respectively called steel dampers, lead dampers and so on. As they have similar hysteresis characteristics, friction dampers are also included in the category of hysteresis dampers.

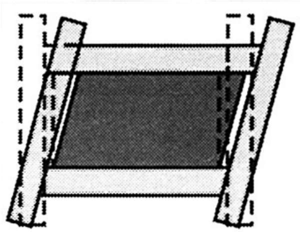
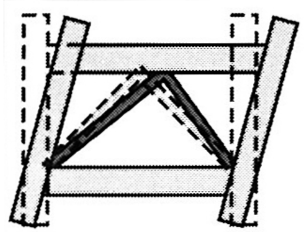
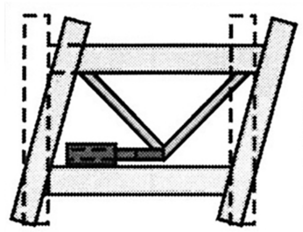
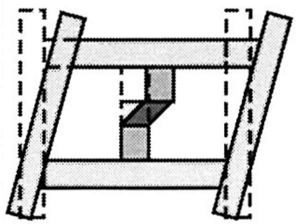
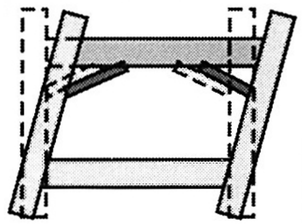
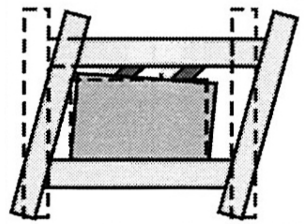
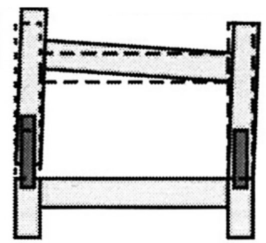
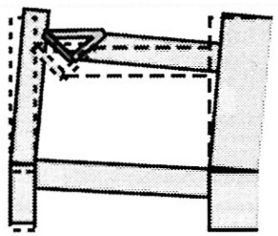
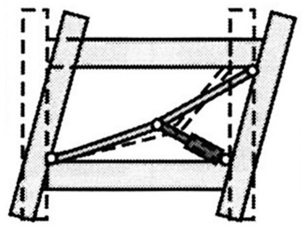
Table 2.1 The types of damper

Dynamics function	Type of damper
Hysteretic dampers (hysteresis energy characteristics devices)	①Steel damper
	②Lead damper
	③Friction damper
Viscous dampers (Viscous damping devices)	④Oil fluid damper
	⑤Viscous damper
	⑥Viscoelastic damper

Table 2.2 The differences of type of hysteretic dampers and viscous dampers

Hysteretic dampers	These dampers use the elasto-plastic hysteresis energy characteristics. Many of them use the capacity of the steel to absorb plastic strain energy. Steel with an low yield point has been developed, and lead, tin and other materials are also used. These are respectively called steel dampers, lead dampers and so on. As they have similar hysteresis characteristics, friction dampers are also included in the category of hysteresis dampers.
Viscous dampers	These dampers use resistance force (damping force) that is proportional to the deformation velocity. They include oil dampers that use fluid resisting force, and viscous dampers that use the shear resistance force of a viscous fluid such as silicon oil. There is also a viscoelastic damper that uses the resistance force of a viscoelastic object such as a polymer material with respect to the shear deformation.

The Various frame types of passive VC in actual use are shown below

	Characteristic	Various frame Type		
Direct connection type	Damping members are connected directly to the main frame above and below the story. The inter-layer deformation is generally transmitted as is to the damping members.	Wall Type 	Brace Type 	Shear Link Type 
Indirect connection type	The inter-layer deformation is transmitted via the bending deformation of the beams, struts and other members. The deformation of the beams and struts makes the deformation of the damping members less than the inter-layer deformation.	Stud Type 	Bracket Type 	Connector Type 
Others	Other methods include those that use the overall deformation of the main frame, and those that use mechanisms to amplify inter-layer deformation. In the case of a column form, the damping effect is obtained while accommodating the pullout of a building with a large aspect ratio. This is also called the step column.	Wall Type 	Beam Type 	Toggle Type 

3. The design of the vibration controlled structure buildings

1. Setting of performance grade

When the design work is begun, it is necessary to set the grade of performance that the building must possess.

An example of setting in the steel frame high-rise building are shown below.
(Case to enhance the seismic resistance performance than usual building.)

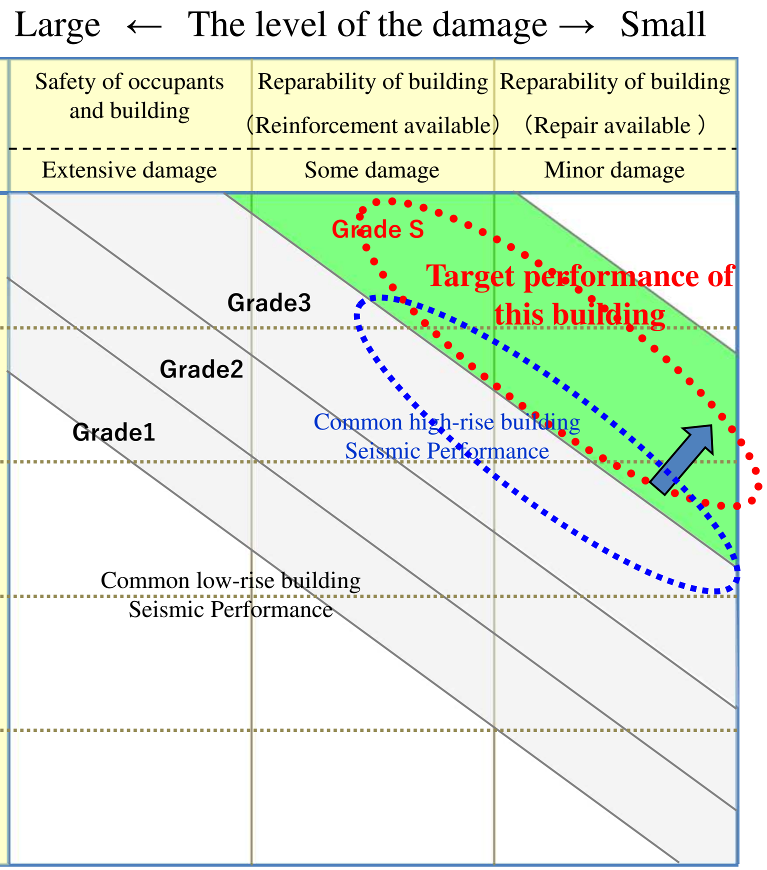
Example for Seismic Performance Grade
(e.g. New Iino Building)

New Iino Building

Small ← Earthquake strength → Large

Seismic Intensity Scale	Maximum acceleration	Possibility of occurrence (at Tokyo)
7	930 gal	1500 years
6 upper	570 gal	600 years
6 lower	350 gal	250 years
5 upper	185 gal	75 years
6 lower	100 gal	25 years

The 1995 Southern Hyogo Prefecture Earthquake



2. Planning of VC structure

Based on the earthquake resistance grade that has been set, the structural planning for the main frame and the damping members is performed.

Based on the seismic performance grade setting, two seismic performance levels can be considered for the main frame.

Case 1: When the main frame is planned so it meets the earthquake resistance performance requirements for a conventional earthquake-resisting structure even with no dampers.

Case 2: When the rigidity of the main frame is intentionally reduced on the presumption that dampers will be provided, so as to ensure that the dampers function more efficiently.

In addition, whether or not the main frame will be damaged in the event of a major earthquake will also have a major impact on the structural planning.

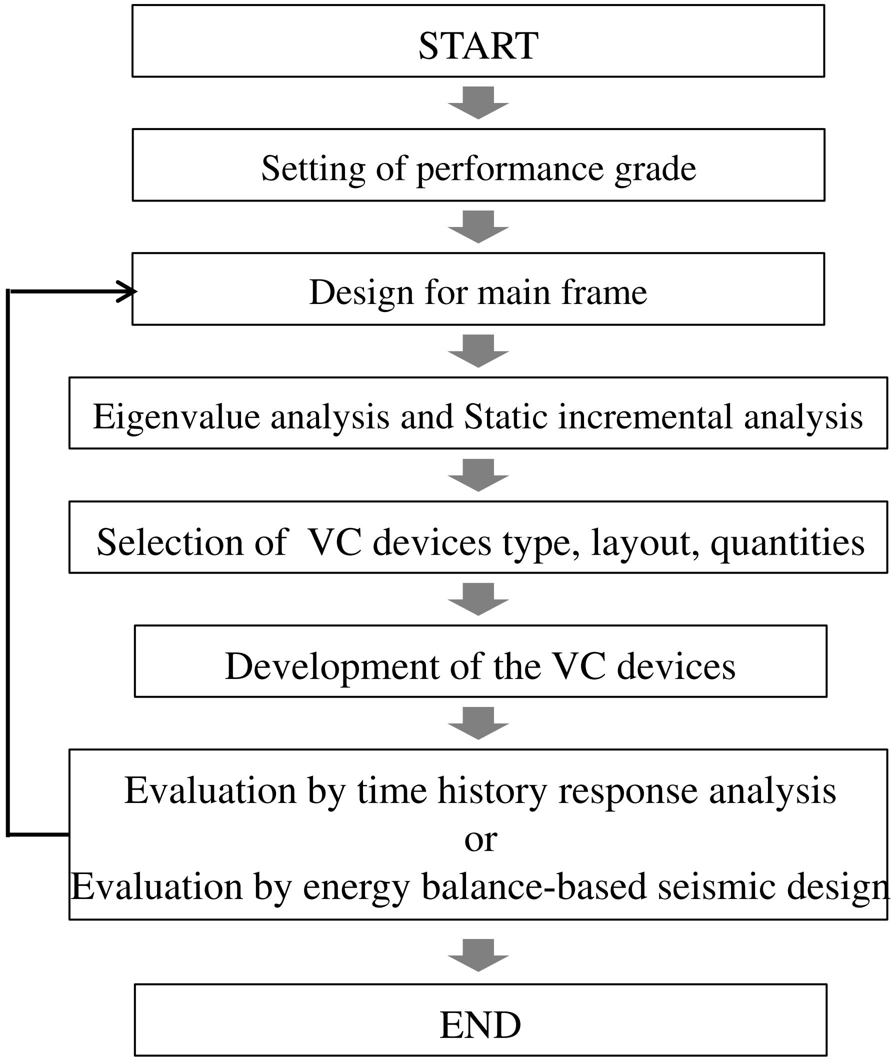


Fig 3.1 Study flow example of VC structure

3. Selection of dampers (by type)

The types of damper members are selected based on the purpose for which they are provided and the target performance (seismic resistance performance grade, etc.).

Installation purpose（Not only seismic performance, consideration of wind load）

① Countermeasure of wind load

② Countermeasure of small to medium-scale earthquakes load

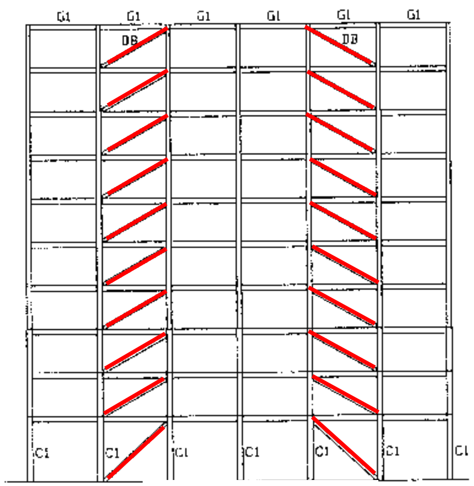
③ Countermeasure of huge-scale earthquakes load

Table 3.1 Considerations for selection of dampers

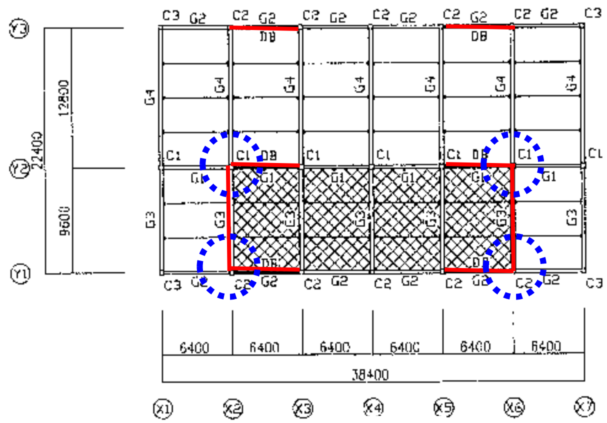
Dynamics function	Type of damper	Considerations for selection
Hysteretic dampers（hysteresis energy characteristics devices）	①Steel damper ②Lead damper ③Friction damper	Steel dampers are effective from a cost-benefit standpoint when it is necessary to absorb a tremendous amount of energy for a short period of time, such as in the event of a major earthquake. However, caution is needed regarding the problem of fatigue with respect to frequently repeated external disturbances such as wind sway.
Viscous dampers（Viscous damping devices）	④Oil fluid damper ⑤Viscous damper ⑥Viscoelastic damper	Viscous and viscoelastic dampers effectively starting from an extremely small area, and there is almost no deterioration in performance with respect to repeated deformation, so they are effective for improving residence performance with respect to long-term continuous wind sway and so on. They are also effective against earthquakes of small to moderate intensity.

4. Considerations for damper layout plan

- The planar configuration should be well-balanced as an overall system so no torsion is produced in the structure.
- The inter-story dampers are effective against the shear deformation portion of the inter-story deformation of the frame, so it is effective to place them in locations where the bending deformation component is small (for instance, on the inside of the structure and in low floor sections).
- When placing dampers on two orthogonal structural planes, note that the diagonal force will be most severe at the columns at the intersecting positions.
- If the aspect ratio is large and bending deformation is great in the building as a whole, it is effective to provide damping members that use the bending deformation of the wall and building, such as outrigger type, column type, wall boundary beam type and so on.
- When conducting design that envisions replacement of dampers in the aftermath of a major earthquake, layout and joint design that enables replacement should be conducted.



SECTION



PLAN

Bracing type damper

Fig.3.2 Example of modeling of VC structure building

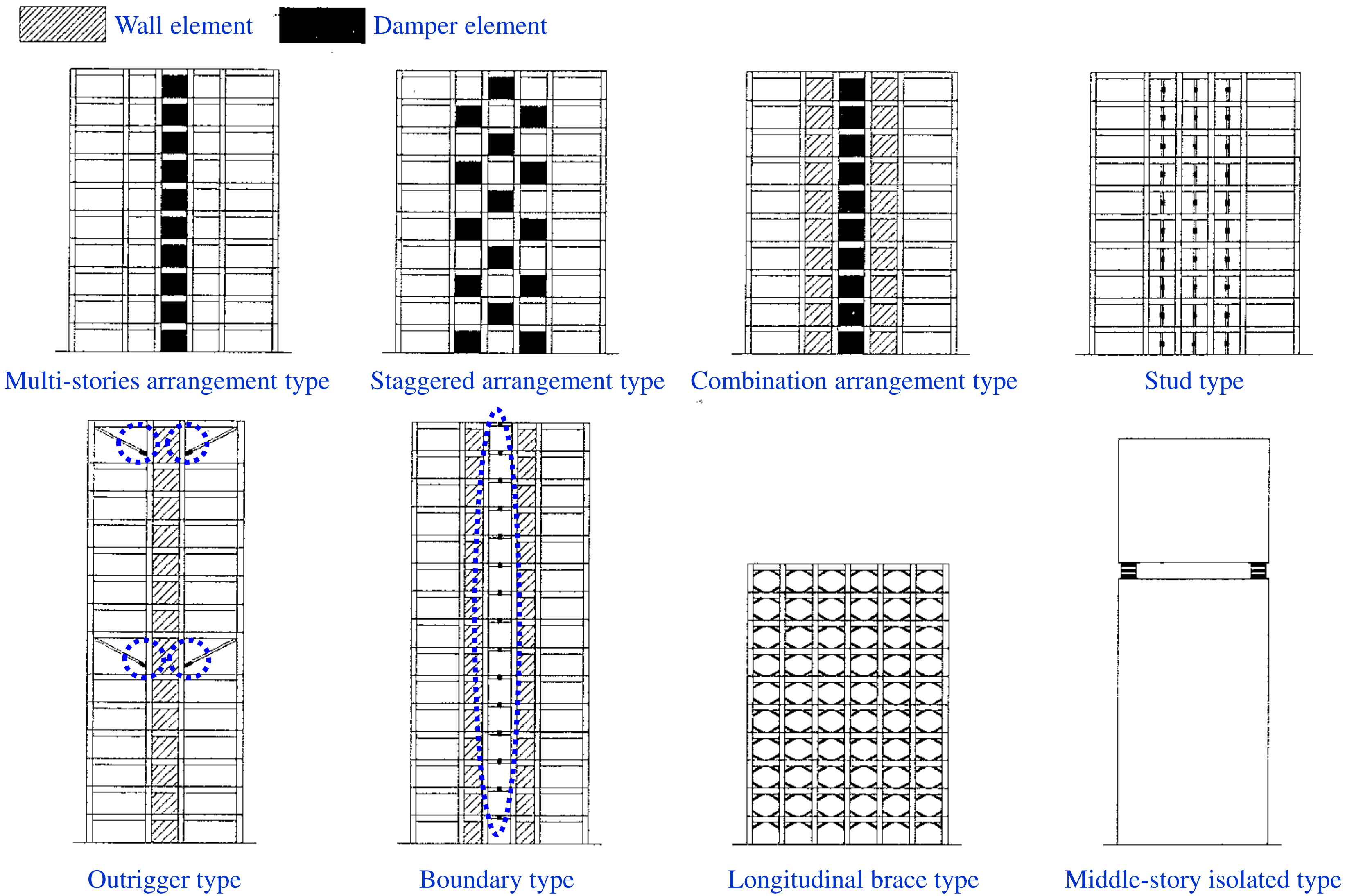


Fig.3.3 Layout example of the damping element

5. Considerations for creation of seismic response analysis models

The seismic response analysis model should appropriately reflect the properties of the building and should be able to evaluate the soundness of the building. When taking steps to simplify the vibration model, special care is needed to ensure that damping effectiveness is not overestimated.

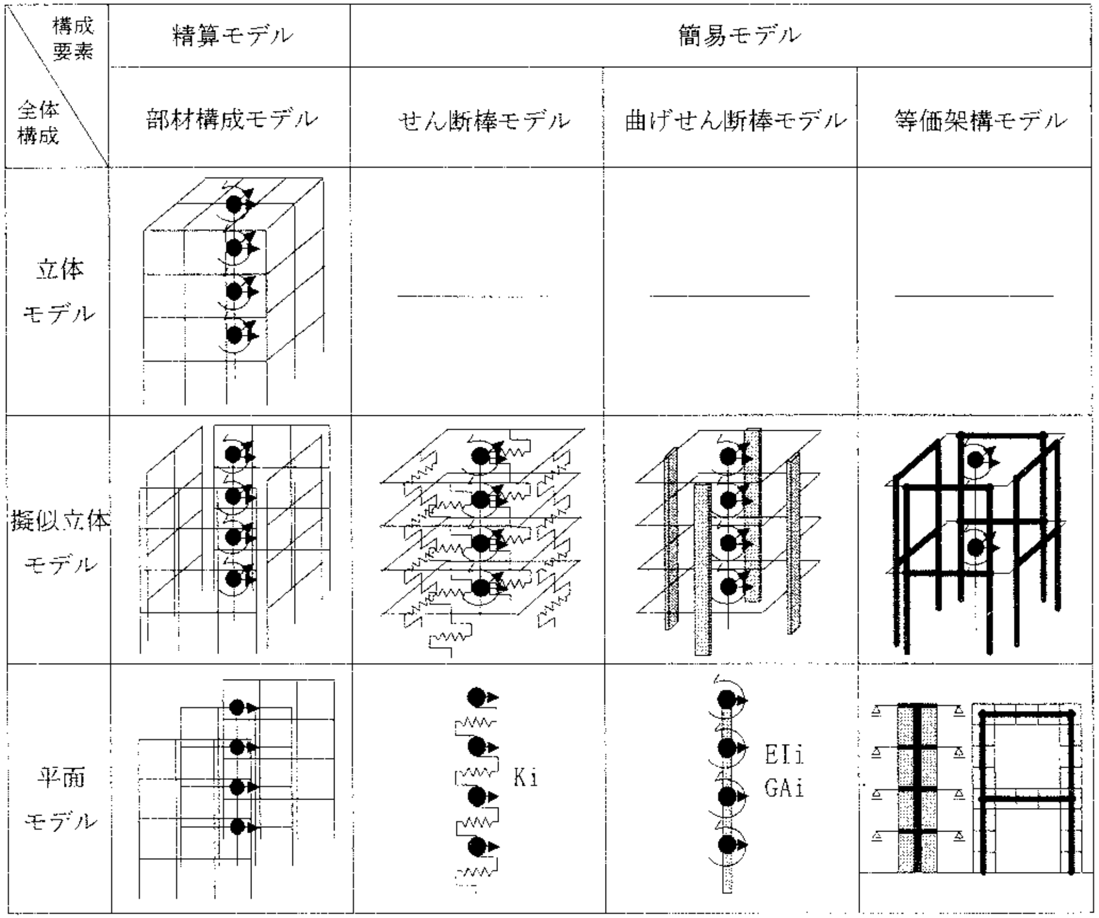


Fig.3.4 Classification of the dynamic analysis model

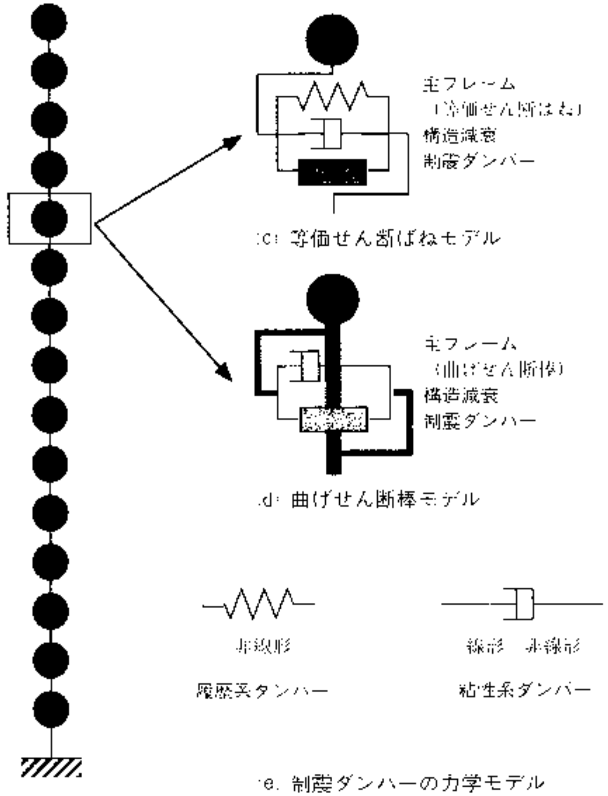


Fig.3.5 Seismic response analysis model
(example of multiple mass-spring model)

6. Considerations for analysis of VC structures

Considerations for analysis to ensure accurate analysis results.

(1) Have the rigidity of the main frame and the effect of the bending deformation component been evaluated appropriately?

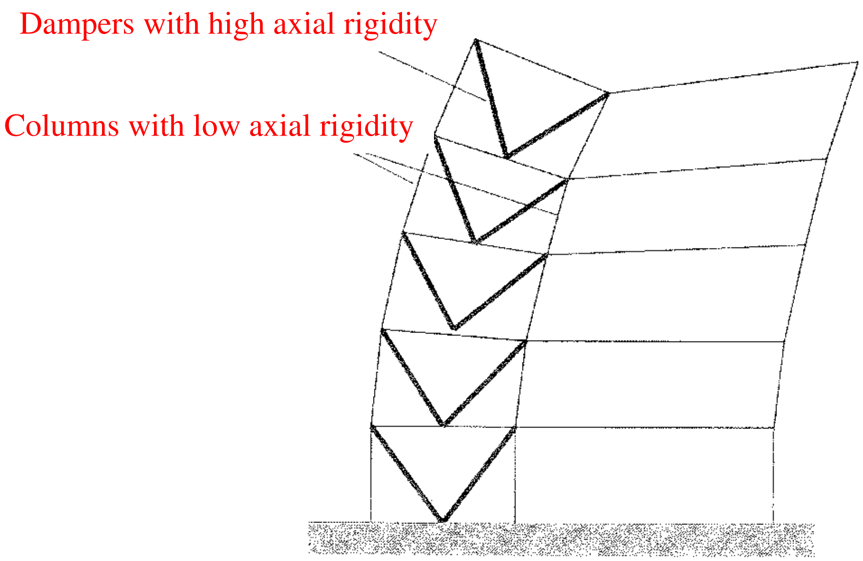


Fig.3.6 Bending behavior of main frame with damper in case of multi-stories arrangement type

When placing VC dampers on multiple stories and so on, the bending component of the frame will be dominant unless the column axial rigidity of the main frame is sufficiently great, and this will reduce the effectiveness of the damping elements that function with respect to the inter-story shear deformation component.

6. Considerations for analysis of VC structures

Considerations for analysis to ensure accurate analysis results.

(2) Are the strength and rigidity of the damping elements, mounting members and peripheral members sufficient?

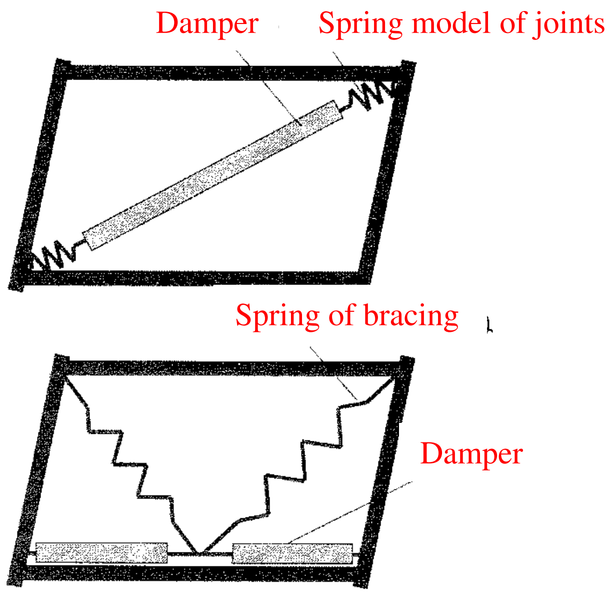


Fig.3.7 Deformation of the joints with damper

If the deformation (rigidity) of the joints between the dampers and the surrounding frame is not evaluated appropriately in the analysis model, there will be a difference between the effectiveness of the dampers in the analysis results and the actual effectiveness.

6. Considerations for analysis of VC structures

Considerations for analysis to ensure accurate analysis results.

(3) Has the safety of the areas where the damping members are attached to the main frame and those joints been confirmed with respect to the maximum bearing force that is applied when the damping members are in service?

For example, in the case of steel dampers, the difference between the increase in yield load caused by strain hardening and the design value for yield load may result in cases in which the reduction effect when the response was calculated is not obtained, and cases in which damage is caused by a force greater than anticipated being applied to the joints.

7. Considerations for design of the dampers

The key points to be considered on the design in order to exhibit the predetermined performance of the damper are shown below.

Table3.2 Consideration points for design of the dampers

Type of damping effect	Devices	Consideration points for design
Hysteresis damping	･Steel damper ･Lead damper	• Study of the low-cycle fatigue characteristics with respect to high winds • Anti-rust treatment • Consideration that is not to apply the axial force • Restrained for buckling • The influence of the welding
Friction damping	･Friction damper	• Prevention of noise during operation
Viscous damping	･Oil fluid damper	• The characteristic change due to the increase of the oil temperature
	･Viscous damper ･Viscoelastic damper	• The characteristic change due to the increase of the element temperature • A study on the influence of characteristic fluctuation • Periodic inspection plan that takes into account the aging

- ■ The energy absorption performance of a **steel damper** is affected by the problem of deceased performance and elements breakage due to repeated deformation, and there are limits to the total amount of energy that can be absorbed. Accordingly, a study is needed to determine whether the absorbed energy during response exceeds the allowable value.
- ■ In an **oil damper** or other **velocity-dependent damper**, a great reaction force is produced due to momentary increases in velocity. Accordingly, measures are needed such as setting an upper limit to the reaction force by means of the opening of a valve at a certain load.
- ■ In some **viscous dampers**, rigidity and attenuation are strongly dependent on temperature. Accordingly, a study is needed with respect to the rise in temperature of the viscous body due to fluctuations in temperature and the conversion of absorbed energy into thermal energy.

8. Confirmation of the criteria of the VC structure

In addition to confirming the criteria for the main frame (restrictions on story drift angle and story plasticity rate), a check should be performed to confirm that the maximum response of the damping members is within the allowable design value for the damping members.

The allowable design value for the dampers are determined by dividing the safety margin that takes into account product variations, account the aging and so on by the ultimate limit value. (Reference 5)

Table3.3 Evaluation points of the ultimate limit state of the dampers

Type of damping effect	Devices	Evaluation points	Ultimate limit state
Hysteresis damping	･Steel damper ･Lead damper	Maximum energy absorption or Maximum number of repetitions or Cumulative plastic deformation (ratio)	• Reduction of history loop area • Occurrence of strength degradation • Occurrence of buckling • Occurrence of the crack and rupture
Friction damping	･Friction damper	Maximum number of repetitions Maximum deformation	• Fracture of the components • Occurrence of strength degradation • Wear deterioration of the friction surface
Viscous damping	･Oil fluid damper ･Viscous damper ･Viscoelastic damper	Maximum stroke(displacement) Maximum reaction load or maximum velocity Maximum deformation or maximum strain	• Fracture of the components • Stroke (deformation) limit • Degradation of the oil viscosity • Lowering of damping performance due to the temperature rise during cyclic loading

4. Design Case Study of Vibration Controlled structure buildings

“Application Example 1 : Office Building”

■Outline of Building

- ✓ Building Name : Totan Muromachi Building
- ✓ Location : Nihonbashi Muromachi, Cyuo-ku, Tokyo, Japan
- ✓ Program : Office
- ✓ Design architect : Azusa Sekkei
- ✓ Structural Engineers : Takenaka Corporation
- ✓ Contractor : Takenaka Corporation
- ✓ Main structure : Steel & SRC construction
  Columns are Concrete Filled Steel-tube
- ✓ Number of floors : 11 stories above the ground
  & 4 underground stories
- ✓ Building height : 54.1m
- ✓ Total floor area : 9,995 m^2
- ✓ Construction Period : November, 2007
  ~ April, 2009

"Application Example 1：Office Building"

■Adopted vibration control devices

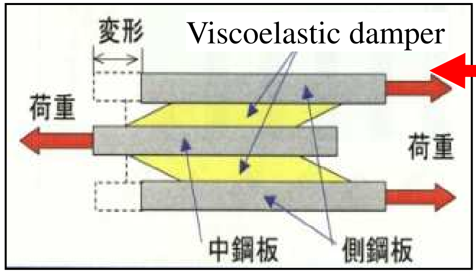
■Oil fluid damper
（with mechanical linkage）

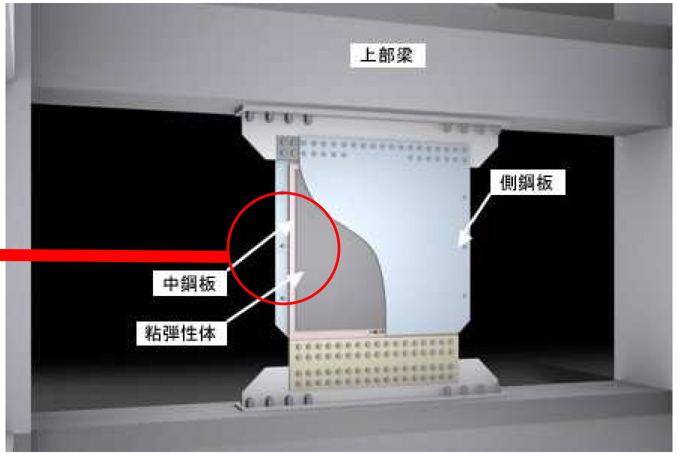
- Amplification mechanism which applies the principle of leverage makes it possible to efficiently absorb energy.

- Due to the shape of the device, an opening can be provided on the brace installation surface. It will be a structure that attracts you with a smart design。

■Viscoelastic damper（Wall Type）

- A viscoelastic damper material is sandwiched between the steel plates separately attached to the upper and lower beams, and energy is absorbed by the movement of the steel plates due to interlayer deformation.





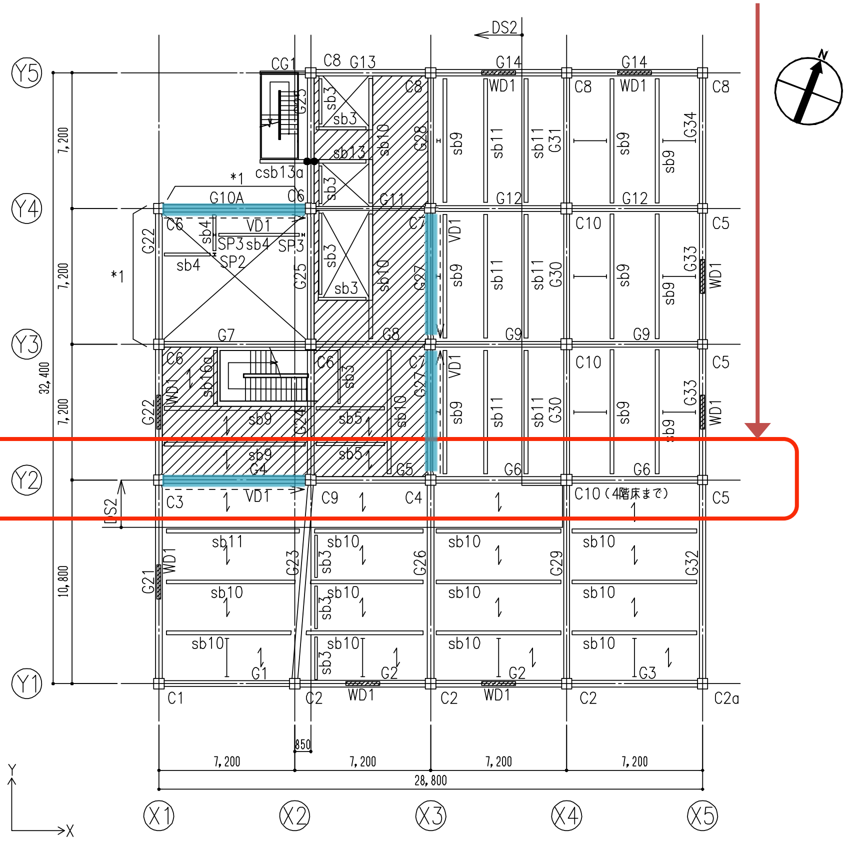
“Application Example 1 : Office Building”

■Frame overview

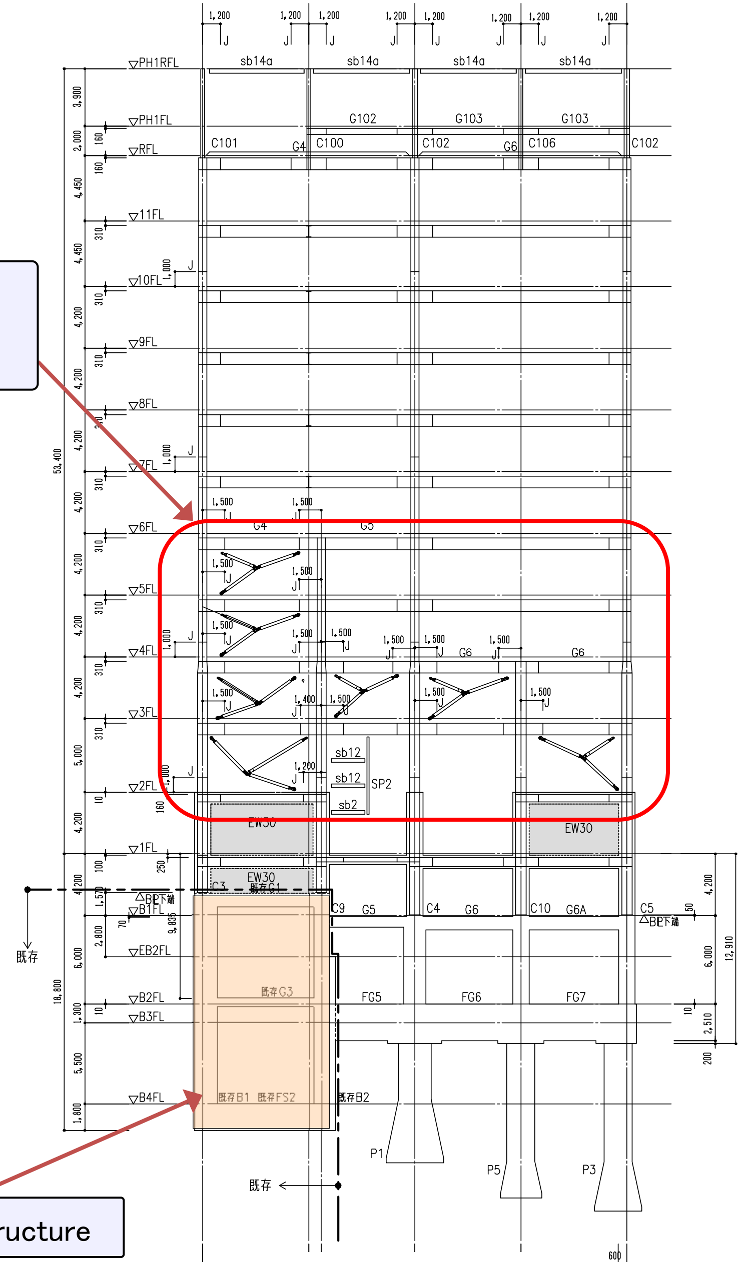
The arrangement of the damping devices

● Oil Fluid Dampers

Maximum Damping Force : 500kN



Floor Framing Plan



Existing structure

Framing Elevation

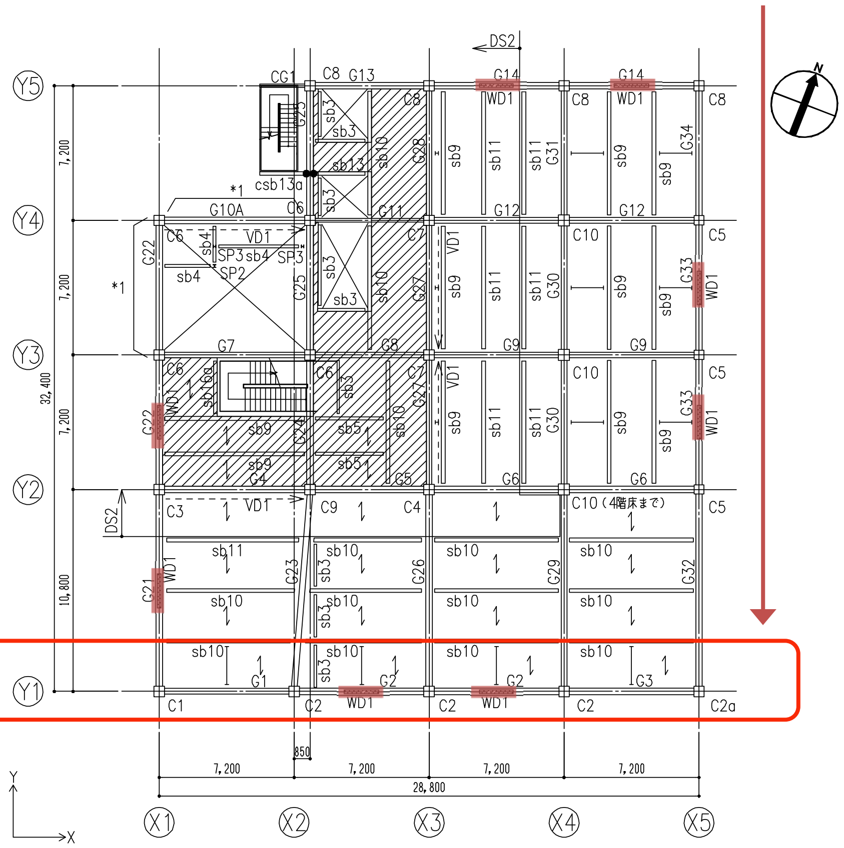
"Application Example 1：Office Building"

■**Frame overview**

The arrangement of the damping devices

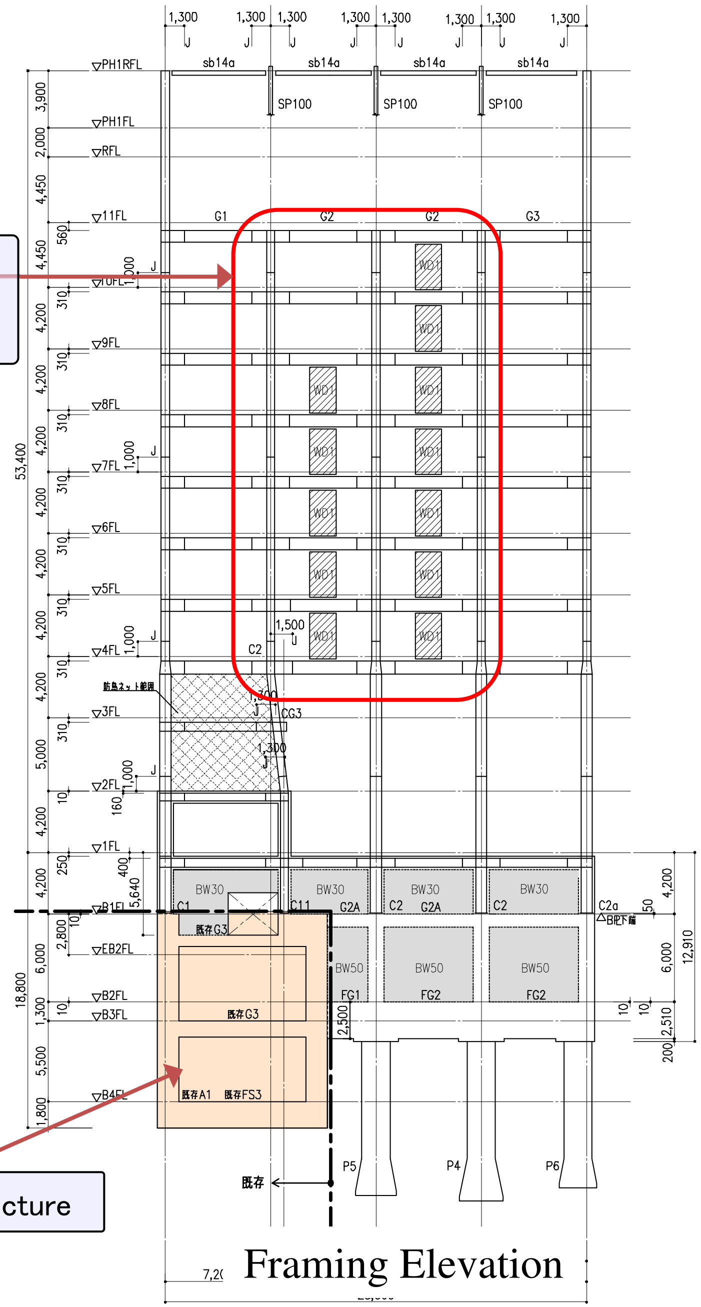
● Viscoelastic dampers

Maximum Damping Force：2000kN



Floor Framing Plan

Existing structure

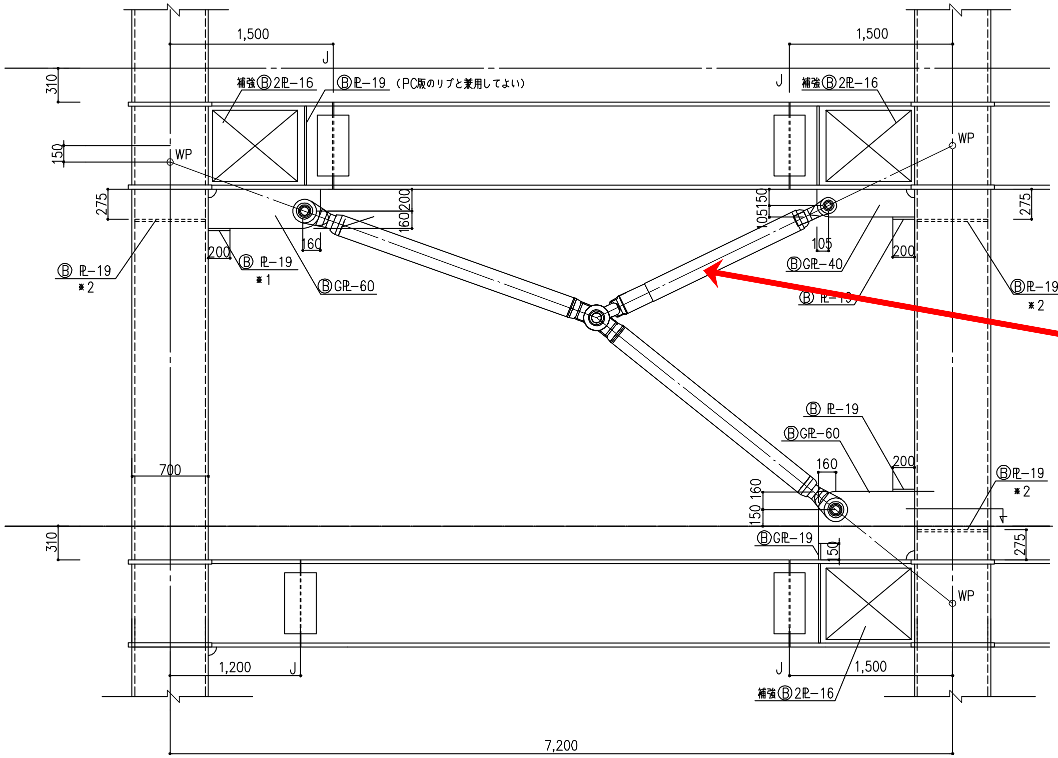


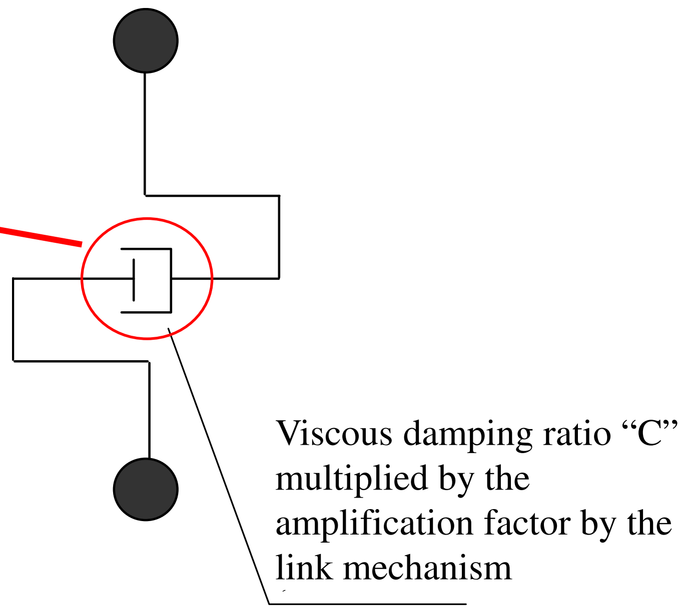
Framing Elevation

"Application Example 1 : Office Building"

■ Modeling for Analysis

- Toggle type (link mechanism) Oil Damper



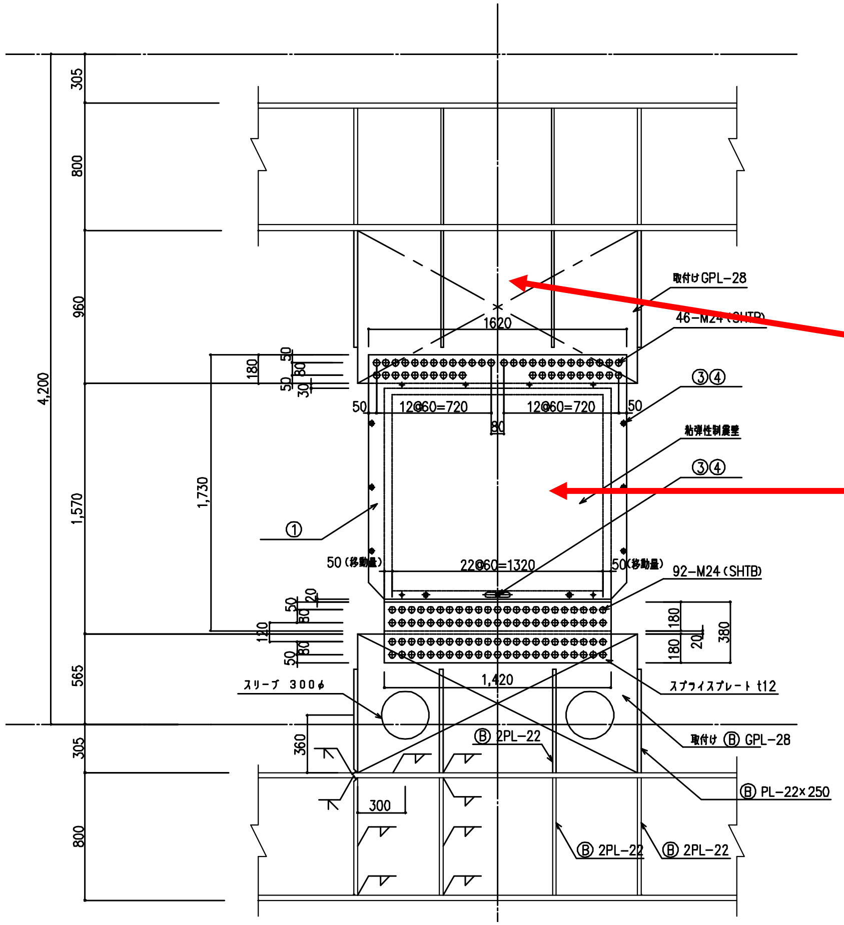


Modeling for analysis of toggle type Oil damper

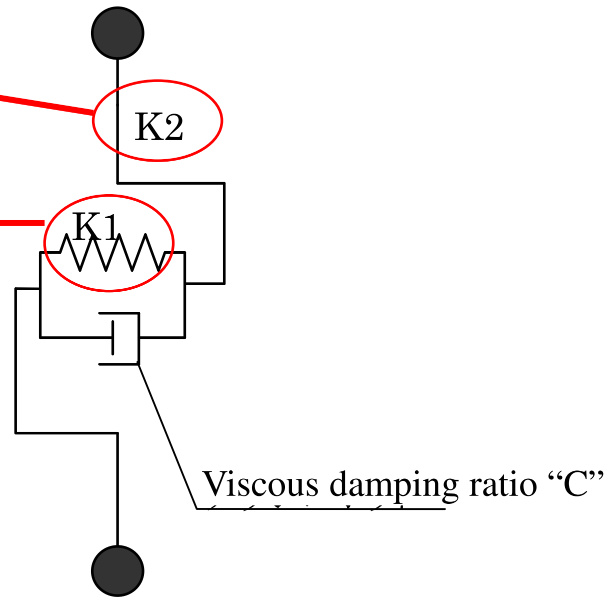
"Application Example 1 : Office Building"

■ Modeling for Analysis

- **Viscoelastic Damper**



- K1: Equivalent stiffness of viscoelastic damper
- K2: Stiffness of the bracket that supports the damper



Modeling for analysis of Viscoelastic damper

“Application Example 1 : Office Building”

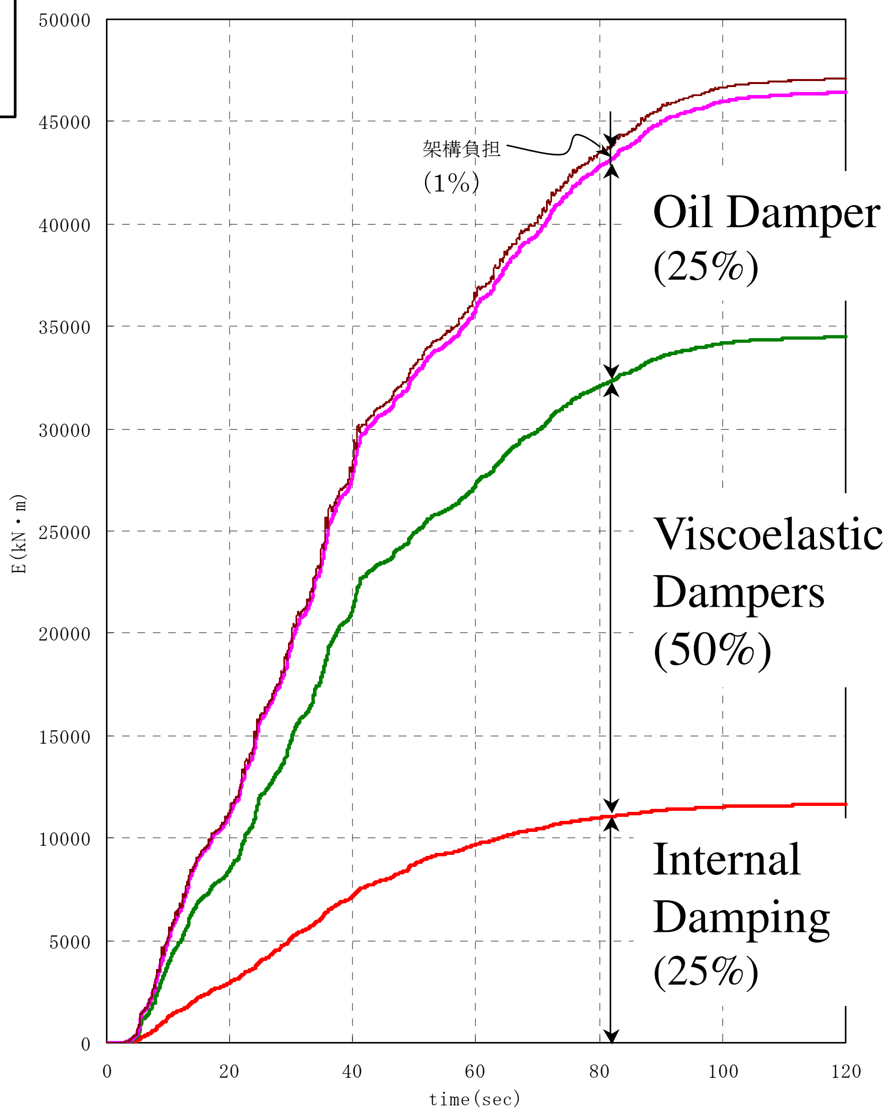
■ Energy absorption ratio of vibration damping devices

●Analysis Examination Conditions

Subject	Detail
Analysis Model	Equivalent Shear lumped mass model
Direction	X-direction
Earthquake	Public announced wave Level-1
Analysis Time	120 sec

●Sharing Ratio

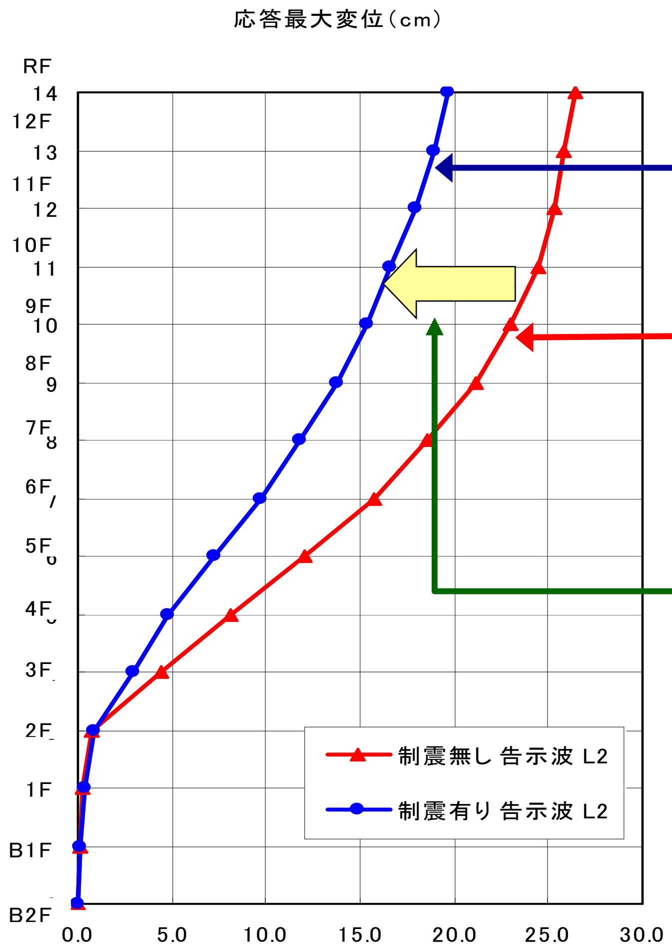
- •Viscoelastic Dampers = about 50%
- •Oil Damper = about 25%
- •Internal Damping = about 25%



Time-history of Cumulative Consumption

“Application Example 1 : Office Building”

■ Effect of damping devices



Valid（With Dumper）

Invalid（Without Dumper）

- It has the effect of approximately 25% to 30% reducing the amount of deformation for the building.
- In addition to the displacement response, the acceleration response value of the floor is also reduced.

Comparison of maximum response displacement with/without damping devices

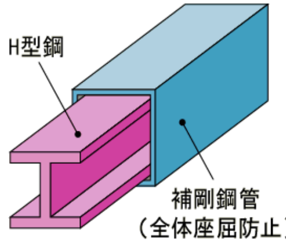
“Application Example 2 : Office Building”

■ Outline of Building

Building Name : Nissan Head Headquarters
Location : Yokohama, Kanagawa
Program: Office
Number of floors: 22 stories above the ground
& 2 underground stories
Main structure : Steel & SRC & RC
Columns are Concrete Filled Steel-tube
Building height : 99.4 m
Total floor area : 92,125 m2
Design & Built : Takenaka Corporation
Construction Period : January, 2007
~ April, 2009

Adopted vibration control devices

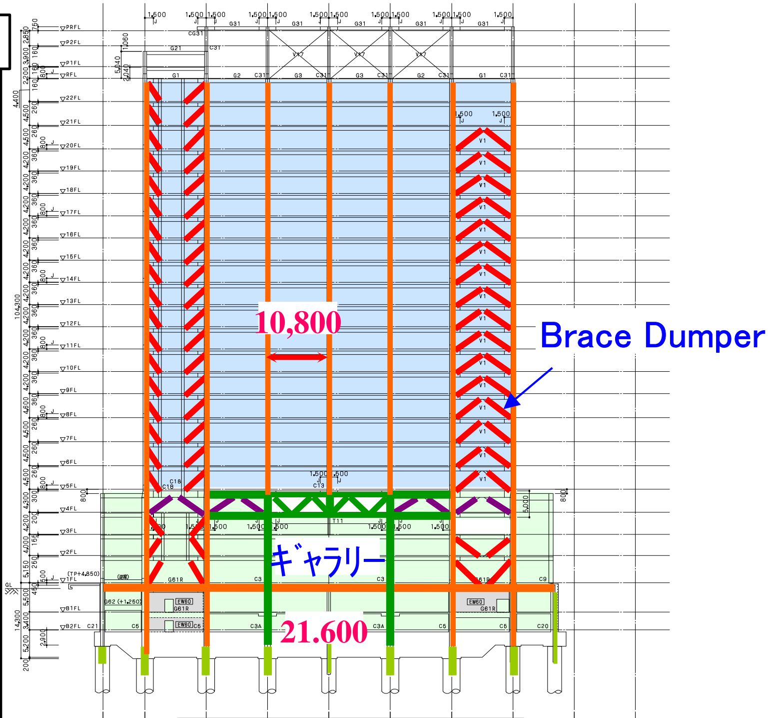
■Takenaka H-shape Steel Buckling-restrained Brace Dumper



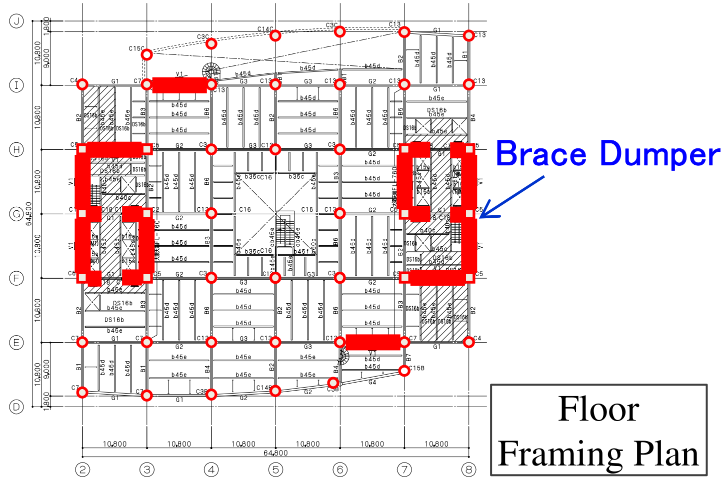
■補剛鋼管によりH鋼ブレースに生じる座屈を拘束する。

■芯材に低降伏点鋼を使用し、地震時に高いエネルギー吸収能力を発揮する。

Buckling-restrained Brace Dumper

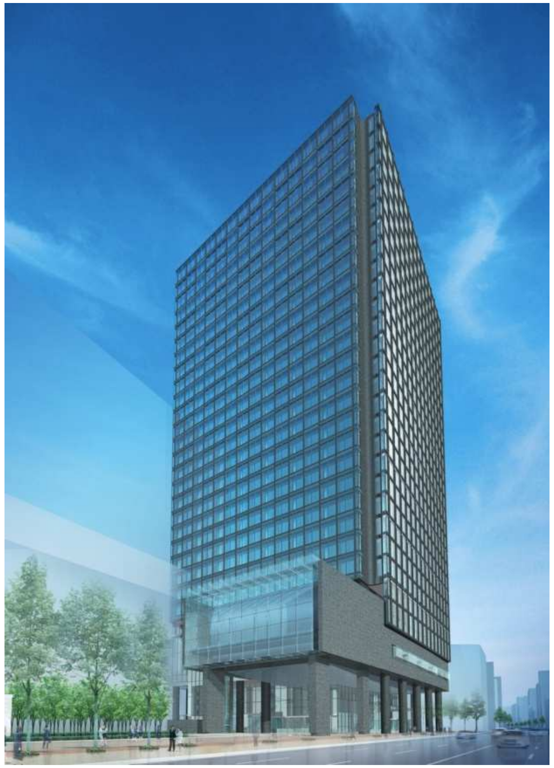


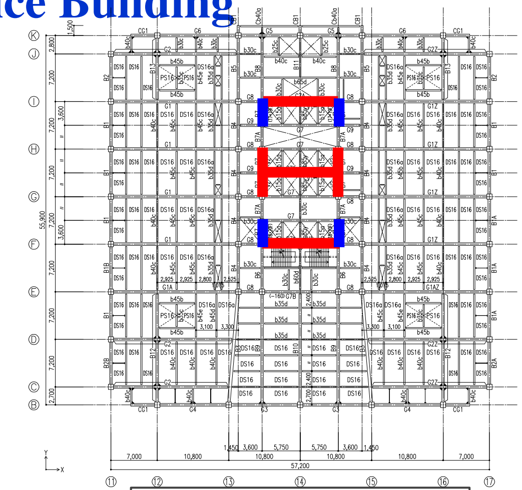
Framing Elevation



Floor Framing Plan

"Application Example 3：Office Building"

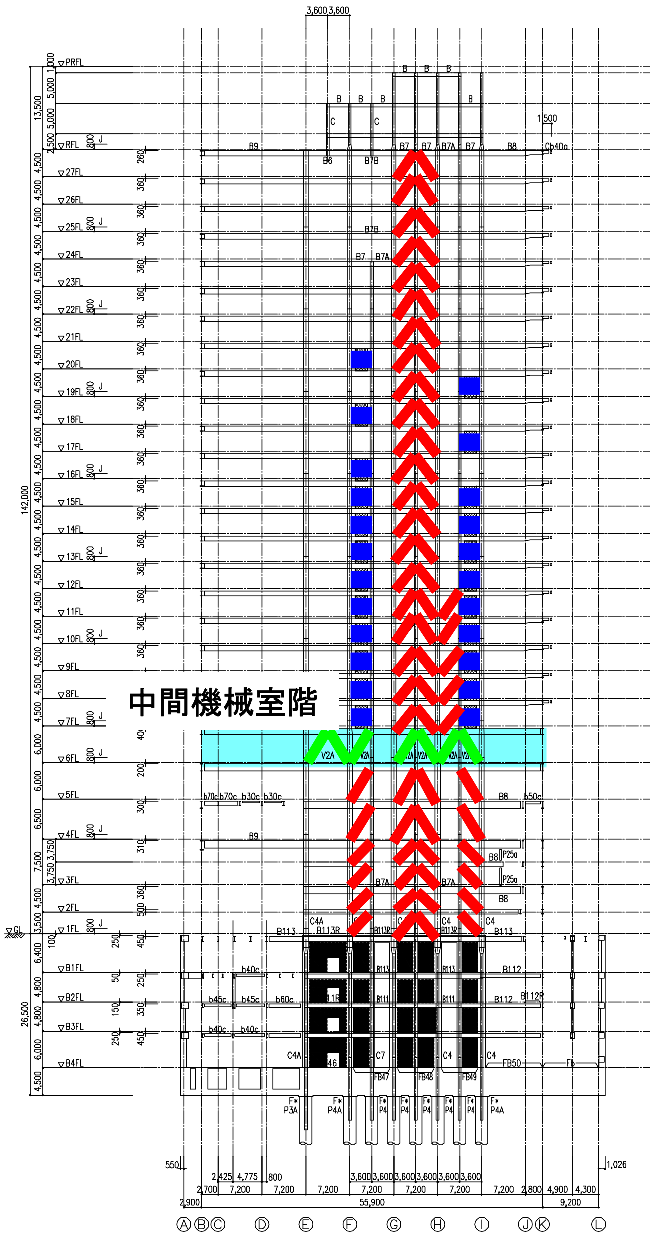




Floor Framing Plan

制震ブレース位置を示す。

は粘性体制震壁位置を示す。



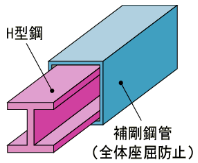
Framing Elevation

■ Outline of Building

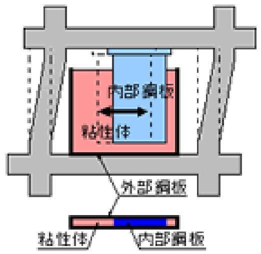
Building Name ：New Iino Building
Location ：Chiyoda, Tokyo
Program： Office
Number of floors：27 stories above the ground & 5 underground stories
Main structure : Steel & SRC & RC
Columns are Concrete Filled Steel-tube
Building height ：142.2 m
Total floor area ： 105,709 m2
Design & Built ：Takenaka Corporation
Construction Period : March, 2009 ~ June, 2011

Adopted vibration control devices

■Takenaka H-shape Steel Buckling-restrained Brace Dumper



■Viscus Dumper



“Application Example 4 : Condominium”

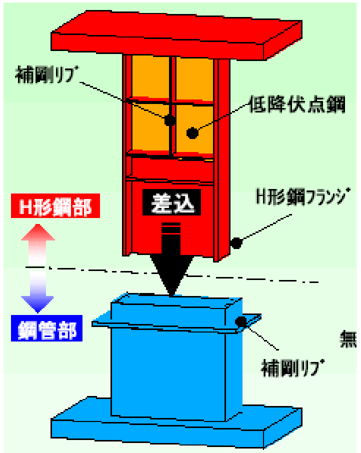
■ Outline of Building

Building Name : Royal Tower Yokohama Tsurumi
Location : Yokohama, Kanagawa
Program : Condominium
Number of floors : 31 stories above the ground & 1 underground stories
Main structure : RC
Building height : 109.0 m
Total floor area : 38,593 m2
Design & Built : Takenaka Corporation
Construction Period : August, 2008 ~ July, 2010

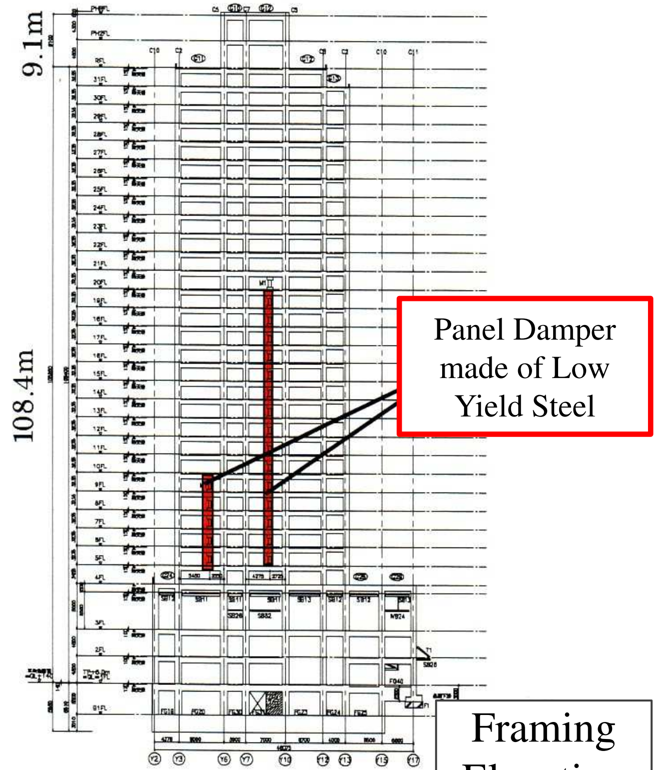
Adopted vibration control devices

■Panel Damper made of Low Yield Steel

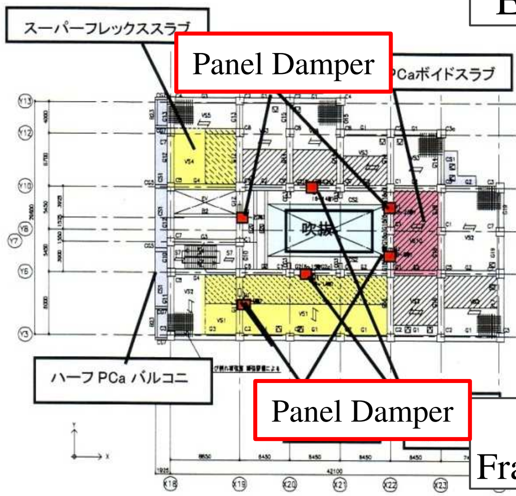
- Only low yield point steel panels yield during extremely rare earthquakes, reducing shaking.



Dumper in RC construction



Framing Elevation



Floor Framing Plan

5. Inspection and maintenance of the damper

1. Principles of quality control of the damping devices

Quality control of the damping devices, "manufacturer", "contractors", "designer" each is to clarify the organization necessary, responsible for their roles responsibly. Each of the role is shown below.

■ The role of the manufacturer

In order to manage, depending on the fabrication process, to clarify the quality control organization and responsible for each step. These management regime, set forth in the fabrication procedure specifications of the damping devices.

■ The role of contractors

It approved the manufacturer of creating quality management organization and production guidelines in the fabrication procedure specifications and production view and the resulting performance, to perform a witness about a specific item in the fabrication process.

■ The role of designers and supervisors

Designers to verify the production procedure specifications, advises against manufacturers and contractors as required. Also, It is confirmed by performance confirmation test the dampers has secured the design performance. Witness the performance verification test with contractors to perform the admission decision.

Flow of quality control of the damping devices

【designer】
Preparation of Design Documents and Permission of the production start

↓

【manufacturer】
Preparation of Fabrication Instruction

↓

Contractors : Approval
Designer : Approval
Supervisor : Acceptance

↓

Fabrication

↓

Performance check by performance confirmation test

↓

【contractors】 Receiving inspection

↓

Construction inspection

↓

Completion inspection

● Entry items (for Fabrication Instruction)

- Quality management system
- Manufacturing process
- Design specifications
- Product specifications (material, shape and dimensions)
- Inspection and test items
- Packing / Transportation
- Submitted documents

● Performance confirmation test ※(sampling or total inspection)

Type of damper	the inspection of the method
Oil fluid damper	shaking test
Viscous damper	shaking test
Viscoelastic damper	Shear test by double shear specimen
Friction damper	Dynamic loading test

● Items of Receiving inspection（example）

製品検査時	製品搬入時
documentary examination (total) Performance check (sampling) Appearance inspection (sampling) Dimensional inspection (sampling) Mark inspection (total)	Mark inspection（total） Appearance inspection（total） Dimensional inspection（sampling）

● Items of Construction inspection（example）

- Assembly Precision (total)
- Tightening status of mounting bolts (total)
- Interference with structure (total)
- appearance (total)
- curing (total)

● Items of Completion inspection（example）

- Interference with structure (total)
- appearance (total)

2. Maintenance concept and purpose

Damping devices are generally in many cases of maintenance-free. However, in order to maintain a predetermined performance, the damping devices are desirable to carry out the maintenance.

During maintenance, the building owner or building administrator to clarify the control system consisting of a vibration damper manufacturers or management company as required, to be carried out deliberately maintained.

Specifically, on the designer has the consent of the owner, create a "maintenance plan", the damping element on the basis of which it is confirmed that can exhibit a function properties. The maintenance plan, the purpose of the maintenance, inspection location, inspection period, inspection items, and can be specified methods of treatment after the inspection.

Table4.1 Inspection type and term

Type of inspection	Timing	Purpose
Periodic inspection	･Every five or ten years	Patrol the building and the appearance of mounting situation and damper own each damper, and intended to improve the early detection and prevention of the risk of abnormal. Building administrator carriy out.
Emergency inspection	･Earthquakes load that exceeds the design value ･Wind load that exceeds the design value ･Fire ･Flooding	Earthquake than assumed in design, the wind is carried out when subjected to fire and flooding. It is intended to confirm the presence or absence of impact on the performance of the damper. As a general rule, a professional inspector performs.

Appendix 1: References

References

（1）国土交通省大臣官房官庁営繕部「建築構造設計基準及び同解説平成16版」2004年

（2）日本建築学会関東支部「免震・制振構造の設計」2007年

（3）日本建築センター「評定・評価を踏まえた高層建築物の構造設計実務」2002年

（4）JSCA「応答制御構造設計法」2000年

（5）日本免震構造協会「パッシブ制振構造設計・施工マニュアル第2版」2005年

（6）Cib「Response Control And Seismic Isolation of Buildings」(邦訳：制振・免震構造) 2006年

（7）郵政事業庁「郵政施設の免震・制振建築」2001年

（8）建築技術「特集：身近になったパッシブ制振構造を学ぶ」2005年8月

（9）JSCA機関誌「主集：制振構造の現状と展望」1998年7月

（10） JSCA「JSCA応答制御構造事例集」2005年

（11）建築研究所/日本鉄鋼連盟「履歴型ダンパー付鋼構造骨組の設計法　報告書」2002年

（12）建築技術編「制震・免震構造マルチガイド」1997年

（13）小堀鐸二「（新版）制振構造　理論と実際」2004年

（14）坪井善昭ほか「広さ・長さ・高さの構造デザイン」2007年

（15）斉藤大樹「耐震・免震・制震のはなし」2005年

（16）日本建築学会「建築構造物の振動制御入門」2010年