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Damage Tolerant Structure

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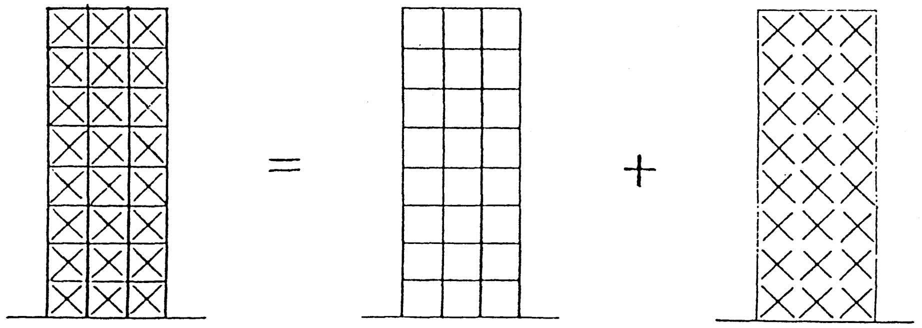
1. Introduction

In the Japanese seismic standards, there are defined two levels of earthquake ground motion and allowable damage for each. For Level 1, medium and small earthquake ground motion, only small damages such as cracks in walls and beams are allowed, while human life and the building structure are to be secured as safe. For Level 2, considering the largest earthquake ground motion, a building structure is allowed to be damaged as far as human life is guaranteed. Current seismic design and its research have been based on this consensus.

Recently, buildings have increased in scale and value, while facilities have grown in expense, such as computers and communication machinery. There are some doubts whether the plastic deformation of a building itself should be allowed for large earthquakes.

In addition, construction activities raise new environmental problems such as ruining rain forests and increasing CO_2 by requiring the production of cement and steel. These problems could be relatively reduced by lengthening the building's life span. It must be meaningful so that large buildings can still be used after large earthquakes instead of reconstructing them.

This paper proposes a new technology for concentrating earthquake damages on certain members and keeping main structure safe for vertical load; therefore the building can still be used simply by replacing certain members after large earthquakes. This technology is theoretically based on Prof. Connor's "Performance based design". This concept suggests that a more rational design could be achieved if each design parameter individually corresponds to each design requirement. In our new structural method, as shown in Fig 1.1, a structure for vertical load supports vertical load and stays elastic during earthquakes, and input earthquake energy is concentrated and absorbed by seismic members. We named this structure a "Damage Tolerant Structure", because seismic members are to be subjected to energy concentration and the structure allows them to be damaged. We also call these parts the "Damage Fuse", and this structure an "Easy Repairable Structure".



Damage Tolerant Structure

Gravity Support Structure in Elastic

Seismic Structure in Elastic-Plastic

Fig. 1.1 Damage Tolerant Structure

2. Seismic Design

In Japan, construction of over 60m-high buildings requires special permission of Ministry of Construction. Table 2.1 summarizes seismic inputs and the criteria of this permission. This is based on the design procedure which were set by Prof. K. Muto about thirty years ago for the first Japanese building over 100m, the 36-story Kasumigaseki building.

Table 2.1 Earthquake Ground Motion and Seismic Design in Japan

	Level 1	Level 2
	Likely earthquake ground motion during building life spand	Possible Largest earthquake ground motion
Static Design	Static Lateral Force for Elestic Design defined on the code. Alowable Stress Design. Interstory Deflection Angle<=1/200	No Criteria for High Rize Steel Buildings. 1.5 times lateral shear capacity to the elastic design force around 1/100 Interstory Deflection Angle for Reinforced Concrete High Rize Buildings.
Dynamic Design	Maximum Velocity of Grand Motion =25cm/s. Interstory Deflection Angle<=1/200. Ductility Factor<=1.0.	Maximum Velocity of Grand Motion =50cm/s. Interstory Deflection Angle<=1/100. Ductility Factor<=2.0.

2.1 Input Earthquake

The strength of earthquake ground motion had been specified using a maximum acceleration until ten years ago, but the response spectra were found not to be uniform when the periods are over 1 second. Nowadays the maximum velocity of ground motion is adopted for the level. This specification has been accepted because the velocity response spectra of several recorded earthquakes become almost uniform when their periods are 1 to 3 seconds. But response spectra of recorded earthquake ground motion have peaks and bottoms, so the building seismic strength can not be measured directly by the response of the time domain analysis. Accordingly, it is not proper to specify the strength of the input earthquake ground motion using the maximum velocity of ground motion. Prof. Akiyama's suggestion of "specified by total earthquake input energy" is more rational, but this has not been adopted officially yet.

2.2 Criteria for Response of Structure

Response results are checked by the response shear force, response displacement and response ductility factor. For Level 1 earthquake ground motion, a structure should stay elastic and the interstory deflection angle should be equal or less than 1/200. For Level 2 earthquake ground motion, the interstory deflection angle should be equal or less than 1/100 and the ductility factor should be equal or less than 2.

The values of interstory deflection angle shown in Table 1 should be appropriate for now and in the future, considering the P-Δ effect, comfortable living and the damage of secondary members such as external walls, glasses and internal walls.

But we have a different idea for ductility factors. Structural materials and construction methods have been developing remarkably these days, there are new structural members which keep high deformability even out of the elastic range, and structural materials that keep their elasticity in large deformation . Therefore, we do not have to stick to the values of ductility factors, 1.0 and 2.0. To be concrete, we think we could admit plastic deformation of certain types of members for Level 1 earthquake ground motion.

3. Development in Structural Materials

Recently, the technologies of steel production have been making significant progress and have realized high strength steel such as a reinforcing bar with 130kg/mm2 strength and structural steel with over 100kg/mm2 strength. Thin steel wires with 350kg/mm2 are also used for car tires. (Fig. 3.1)

In other fields, high strength concrete, ceramics as new material, carbon fiber and fiber reinforced plastic have been developed and put into experimental use.

One of the big goals of the recent research on structural steel has been to enhance its strength. Young's modulus for steel is constant irrespective of strength, so the higher strength steel has the wider elastic strain region. The main structure of a Damage Tolerant Structure depends on the high elasticity of this high strength steel. On the other hand, energy absorbing members of Damage Tolerant Structure depend on materials with low yield, narrow elastic strain region and high ductility.

Accordingly, we find a new type of structure could be created by using new materials. So we can say "Material drives a new structure".

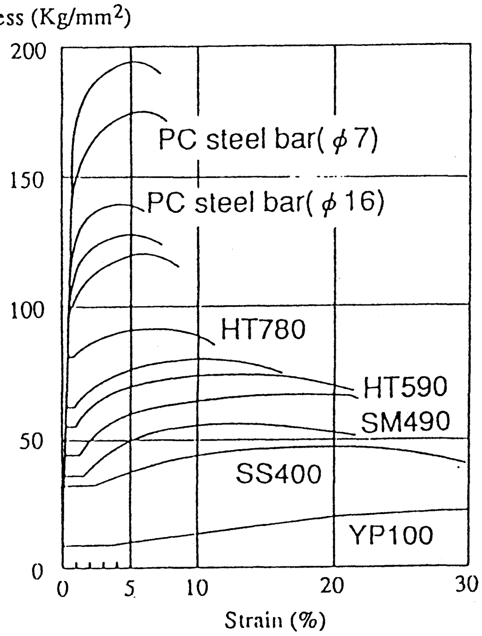


Fig. 3.1 Stress Strain Relationships of Several Kinds of Steel

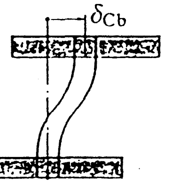
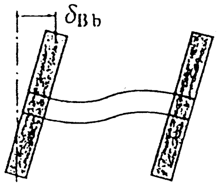
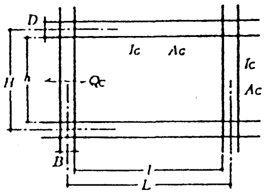
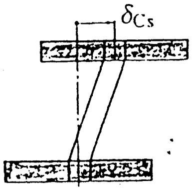
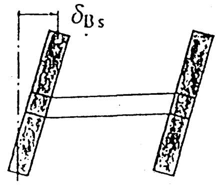
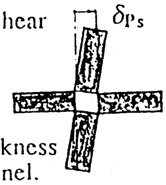
4. Properties of Frame Structure

4.1 Deformation of Tall Building

The deformation of the frame of a tall building caused by lateral force such as earthquake or wind, is divided into two components, the whole structural bending deformation and the shear deformation of the frame. On the assumption that a building is one pole, the whole structural bending deformation is regarded as the bending deformation caused by the expansion and contraction of columns. Shear deformation of the frame is rhomboid distortion which is composed of five components, bending deformation and shear deformation of a column, bending deformation and shear deformation of a beam, and shear deformation of a shear panel, as shown in Table 4.1.

The interstory deflection of the low-story part of a tall building is mainly caused by shear deformation of the frames, and that of the high-story part is mostly caused by whole structural bending deformation. The ratio of whole structural bending deformation to shear deformation of the frames is changed not only by the vertical position but also by the aspect ratio of the building and the lengths and sectional shapes of beams and columns.

Table 4.1 The 5 Components of Frame Shear Deformation

Column Bending  $\delta_{Cb} = \frac{h^3}{12EI_C} Q_C$	Beam Bending  $\delta_{Bb} = \frac{l^3}{12EI_B} \left(\frac{H}{L}\right)^2 Q_C$	 $\delta = \delta_{Cb} + \delta_{Cs} + \delta_{Bb} + \delta_{Bs} + \delta_{Ps}$
Column Shear  $\delta_{Cs} = \frac{h}{GA_c} Q_C$	Beam Shear  $\delta_{Bs} = \frac{l}{GA_B} \left(\frac{H}{L}\right)^2 Q_C$	Panel Shear  t is thickness of panel. $\delta_{Ps} = \frac{h^2}{GBD\, t_P} \left[\frac{1 - \frac{BD}{lh}}{1 + \frac{B}{l}} \right]^2 Q_C$

4.2 Rotation Angle at Beam End

Forcusing on the interstory deflection of the middle-story part of a tall building, the ratio of Interstory deflection caused by whole structural bending deformation to Shear deformation of a frame is assumed to be 1:9 to 3:7.

A column has a shorter length and larger sectional area than a beam to support vertical load and avoid plastic deformation during earthquakes. Therefore the deformation of a column is smaller than that of a beam.

Among the five components composing shear deformation of a frame, the summation of bending deformation and shear deformation of a column and shear deformation of a shear panel is assumed to hold in the range of 30~40%, and the summation of bending deformation and shear deformation of a beam is from 60~70%. With these values, the beam deformation is calculated to be 42~63% of the interstory deflection. When the beam deformation is assumed to be divided into the bending deformation and shear deformation by the ratio of 9:1 to 7:3, the bending deformation of a beam is calculated to be 30~60% of the interstory deflection.

This percentage becomes larger when a beam yields in a structure with strong columns and weak beams. The bending deformation of a beam shall be up to 80 % of the interstory deflection.

Consequently, when a structure stays elastic for Level 1 earthquake ground motion, a 3/1000 deflection angle (60% of 1/200 interstory deflection angle) may occur at the beam end. When a structure becomes plastic for Level 2 earthquake ground motion, an 8/1000 deflection angle (80% of 1/100 interstory deflection angle) may occur at the beam end.

In our structural method, we use high strength steel for columns and beams and keep them elastic during Level 2 earthquakes. Therefore 60% of 1/100 interstory deflection angle, which is 6/1000 deflection angle, may occur at the beam end.

When we calculate the interstory deflection excluding the whole structural bending deformation, 3/1000 turns out to be 4/1000, 8/1000 to 9/1000 and 6/1000 to 7/1000.

Table 4.2 Material Properties

Name	Yield Strength	Maximum Strength
SS400	24 Kg/mm2	41Kg/mm2
SM490	33 Kg/mm2	50Kg/mm2
HT590	48 Kg/mm2	60Kg/mm2
HT780	64 Kg/mm2	80Kg/mm2

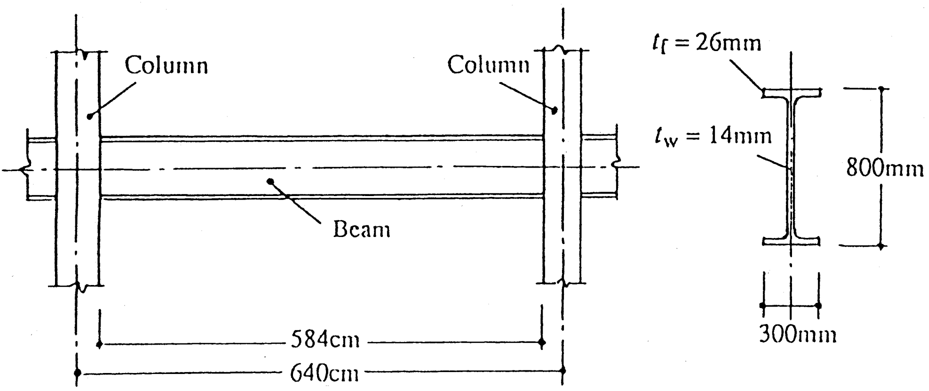


Fig. 4.1 Tipical Beam using Stell Tall Building

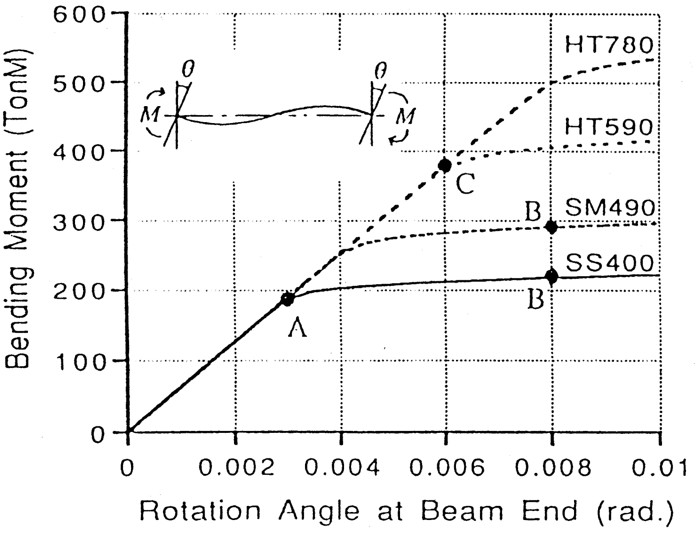


Fig. 4.2 Relationships of Bending Moment
vs. Rotation Angle at Beam End

4.3 Strain Distribution of Beam Flange

When a frame subjected to a lateral force causing interstory deflection of 1/100 and 1/200, the rotation angles produced at the beam end are as described in 4.2. The rotation angle is the integration of the curvature occurring in a beam, and the strain of a flange is calculated by multiplying the curvature by half of the beam depth.

Here we indicate the relationship between the rotation angle at the beam end and the strain distribution along a flange respectively for four different types of steel, their yield stress being listed in Table 4.2. SS400 and SM490 are commonly used in Japan and HT590 and HT780 are used for special plants such as pressure vessels which need high strengths. The length and shape of the section of the beam are 5.84M, H-800*300*14*26 as shown in Fig.4.1. Fig. 4.2 describes the relationship between the bending moment and the rotation angle at beam end. Point A corresponds to 1/200 interstory deflection angle, and almost all the steels are in an elastic condition. Point B corresponds to 1/100 interstory deflection angle of SS400 and SM490, and the rotation angle at the beam end is 8/1000. Point C indicates HT590 and HT780, selected for our proposed structure, and when the rotation angle at beam end is 6/1000, both steels are in an elastic condition.

Fig. 4.3 shows the strain distribution along the flange of each beam at Point B and C. There are four lines in this figure, but SS400 and SS490 have nearly the same curve , and HT590 and HT780 have nearly the same straight line. These lines indicate that in case of SS400 and SS490, large strain concentrations occur at the beam ends. In case of HT590 and HT780, strain is distributed linearly along the whole member because of their large elastic strain ranges.

These results are the strain distribution along the flange when the interstory deflection of a frame is 1/100. We found the high strength steel may be subjected to this deformation without becoming plastic. Consequently, plastic deformability is not required for a member using high strength steel. Keeping main structure elastic until 1/100 deformation for Level 2 earthquake ground motion has further advantages: the stiffness of every story is secured, no certain story is destroyed by energy concentration and the whole building would be deformed smoothly.

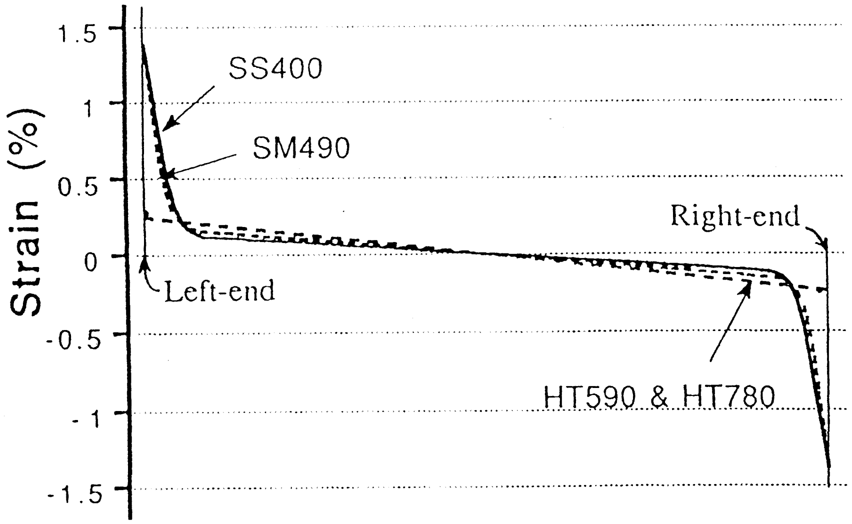


Fig. 4.3 Strain Distribution along the Flange of each Beam at point B and C in Fig. 4.2

5. Damper

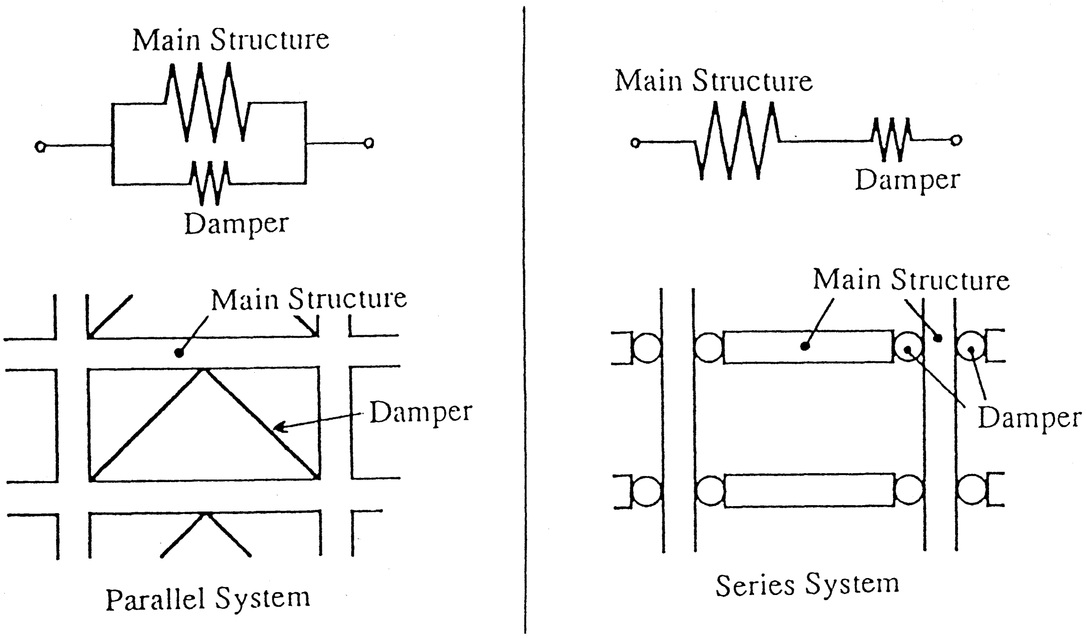
If we build a structure only with high strength and high elasticity material, the structure shall have elastic behavior. Consequently, the structure shall have no energy absorption and this would be a serious problem in seismic design. Dampers become essential for this type of structure to absorb earthquake or wind energy and reduce its response.

We adopted an unbond brace as a damper, which is a hysteretic damper and composed of low yield strength steel. An unbond brace is characterized by a stable hysteritic loop without buckling, as the details mentioned in Appendix A. Low yield strength steel has a small elastic strain range and wide plastic strain range, so it works effectively in energy absorption.

There are two ways of attaching dampers to a main structure: a series system or a parallel system, as shown in Fig. 5.1. Series systems fit structures with high stiffness and no ductility. The failure of a main structure could be avoided by lengthening the structure's natural period and by concentrating the deformation on the highly deformable dampers. But series system is no good for the main structure with low stiffness, because the total stiffness is lowered by this system.

Parallel systems fit structures with low stiffness and large elasticity, and we apply this system to our structure. In a parallel system, the initial stiffness s is the sum of stiffnesses of the main structure and the dampers, then the stiffness becoming higher for small deformations. The dampers work efficiently because structural deformation is transmitted into dampers directly.

Further more, the main structure stays elastic during an earthquake, so the main structure returns to its original shape merely by replacing the dampers. This characteristic is very important and therefore we have named this structure a "Damage Tolerant Structure".



Parallel System

Series System

Fig. 5.1 System of Main Structure and Damper

6. Example of Structural Design

We introduce an example of an application based on the concept of a "damage tolerant structure". The H-Project, planned in Tokyo, is a 40-story office building, 180 m in height and 50 m by 50 m of a typical floor as shown in Fig. 6.1. The frame system shown in Fig. 6.2 is proposed for the H-Project. It is a high-strength, high-elasticity frame with HT780 columns and HT590 beams. The unbond braces described in Chapter 5, made of lowyield strength steel, are used as dampers. The unbond braces are arranged in all external sides of the building to provide a homogeneous structure.

Nonlinear analysis were performed for the model, shown in Fig. 6.3, by assuming that the stress-strain relation of the steel is bilinear. The results of the nonlinear analysis are shown in Fig. 6.4. The unbond braces first yielded at 1/400 interstory deformation angle, and the beams yielded at 1/100.

This structural system can be realized if the thickness of the steel plate is designed so that the response displacement angle does not exceed 1/100 for Level 2 earthquake ground motion.

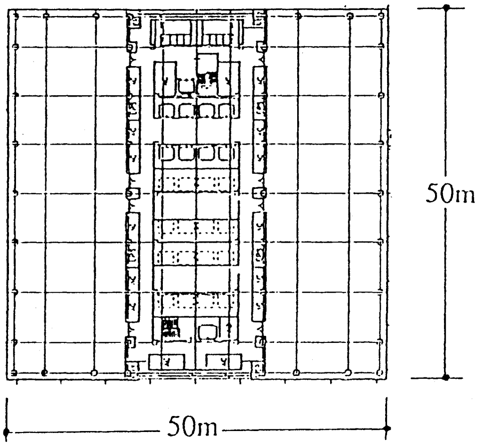


Fig. 6.1 Plan of H-Project

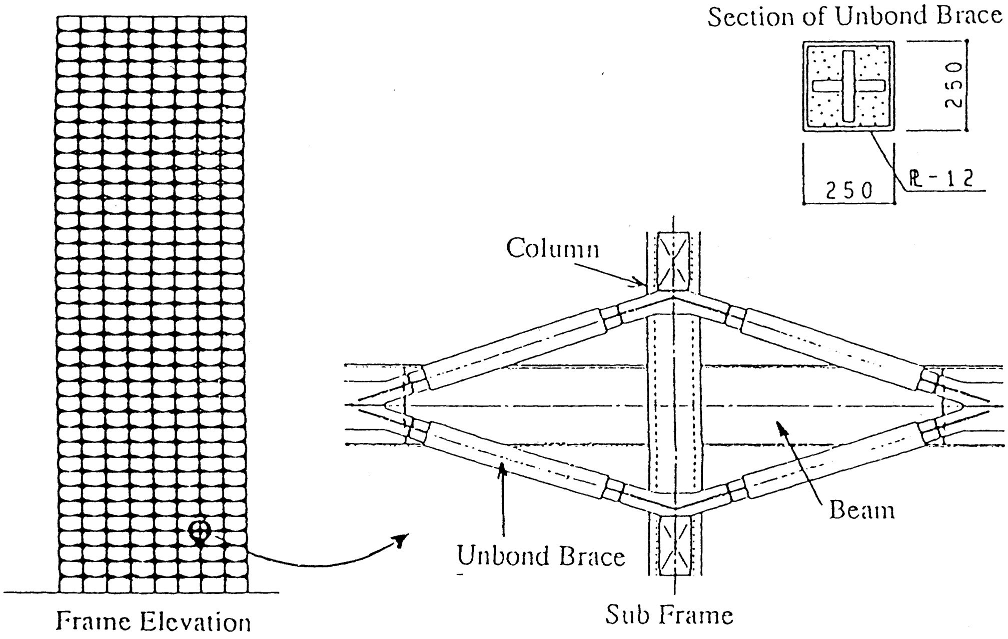
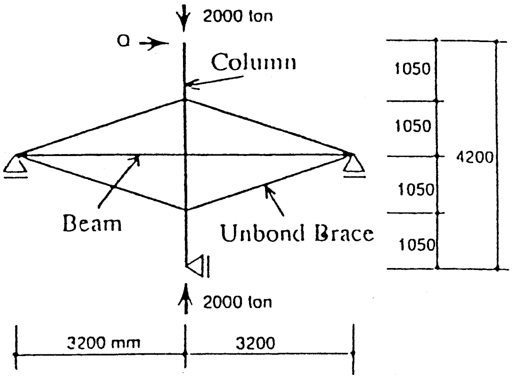


Fig. 6.2 Frame System proposed to the H-Project



Column (H-558x467x80x100, σ_y=64Kg/mm^2)
Beam (H-800x300x14x26, σ_y=48Kg/mm^2)
Unbond Brace (Pl-35.2x200, σ_y=10Kg/mm^2).

Fig. 6.3 Analysis Model of Sub Frame

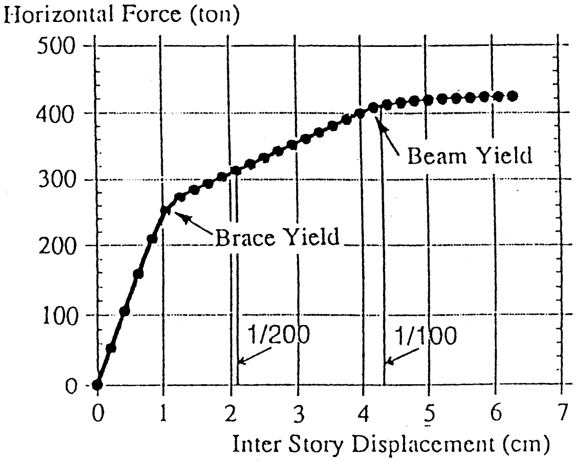


Fig. 6.4 Relationships of Horizontal Force and Inter Story Displacement

7. Experimental Study

We are preparing for an experiment to implement our proposal on the Hproject. This experiment is scheduled for October 1992. The specimen is on a scale of 1/2.3 actual size, and has a cross-shaped substructure according to Chapter 6. Fig.7.1 is the illustration of the experimental apparatus. The right and left beam ends are supported by horizontal rollers, the bottom of the column is supported by a vertical roller and the column head is subjected to lateral force using a 100 ton-jack. In the experiment, the interstory deformation of +- 1/100 angle is applied on the column head repeatedly 10 times, and the mechanical properties of the frame are examined.

We will examine 5 types of specimens as listed in Table 7.1. No.1 to No.4 are pure moment resisting frames as illustrated in Fig. 7.2, and each specimen is made of a different strength steel. The 5 components of the shear deformation of the frame are calculated for these specimens and the results are listed in Table 7.2. The bending deformation of the beam turns out to be 53%.

No.5 uses the same strength steel as No.2 and unbond braces.

Proceeding the experiment, we performed elasto-plastic analysis for these five specimens and have indicated these results in Fig.7.4. In No.1 and No.2, HT780 and HT590 are used for columns and the beams, and the frame were deformed elastically until 1/100 interstory deformation. In No.3 and No.4, SM490 and SS400 are used, and the frames become plastic at over 1/200 deformation.

For specimen No.5, the unbond braces of low yield strength steel start to become plastic at a very small deflection, thus we confirm their energy absorbing capacity.

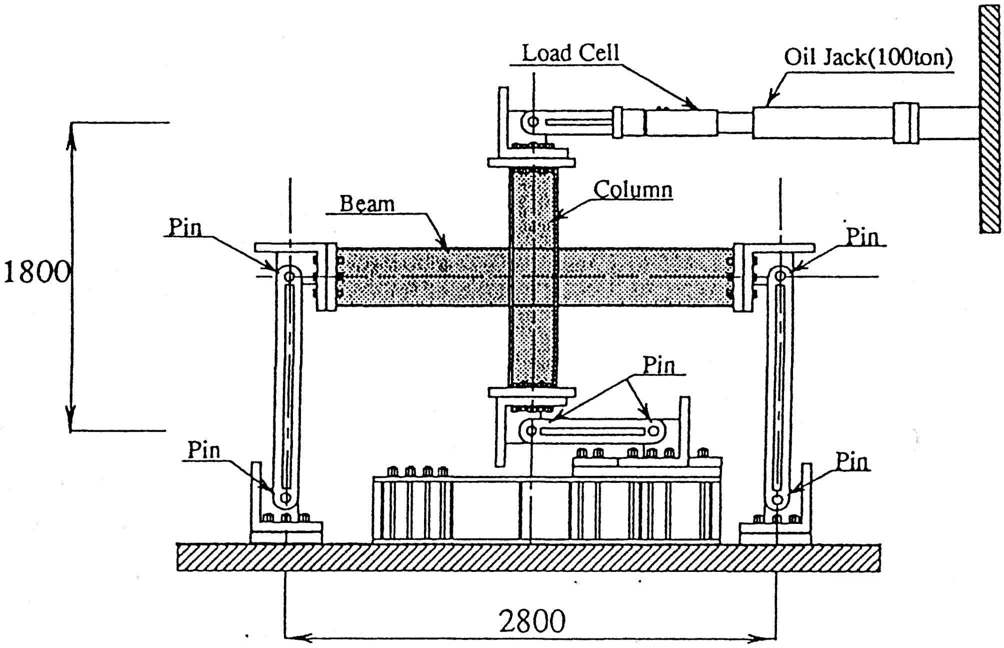


Fig. 7.1 Experimental Apparatus

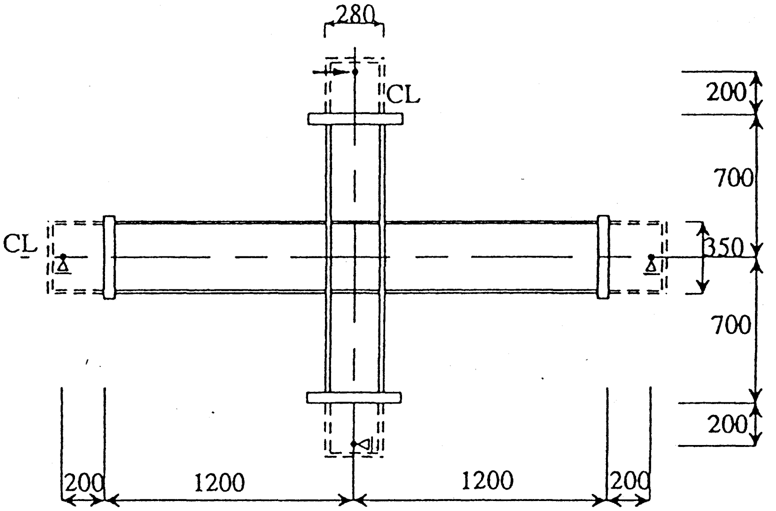


Fig. 7.2 Specimens of No.1 - No.4

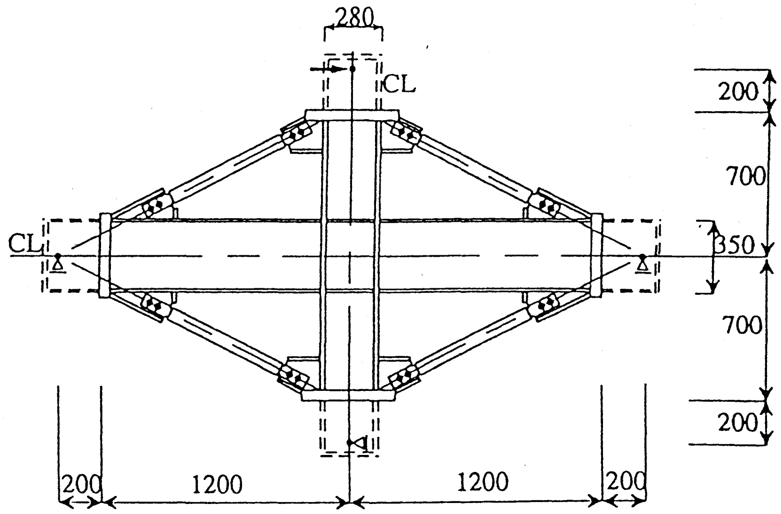


Fig. 7.3 Specimen No.5

Table 7.1 List of the Specimens

Number	Frame Type	Steel used for Columns	Steel used for Beams
No.1	*Pure Frame*	*HT780* (σy =72 Kg/mm^2)	*HT780* (σy =72 Kg/mm^2)
No.2	*Pure Frame*	*HT780* (σy =72 Kg/mm^2)	*HT590* (σy =54 Kg/mm^2)
No.3	*Pure Frame*	*SM490* (σy =36 Kg/mm^2)	*SM490* (σy =36 Kg/mm^2)
No.4	*Pure Frame*	*SM490* (σy =36 Kg/mm^2)	*SS400* (σy =26 Kg/mm^2)
No.5	*With Braces*	*HT780* (σy =72 Kg/mm^2)	*HT590* (σy =54 Kg/mm^2)
	Unbond Braces using YP10 for core plate (σy =10 Kg/mm^2).		

Table 7.2
5 Components of Elastic Frame Shear Deformation

	Bending	Shear
Column	*12.7%*	*5.9%*
Beam	*53.2%*	*9.4%*
Panel	----	*18.8%*

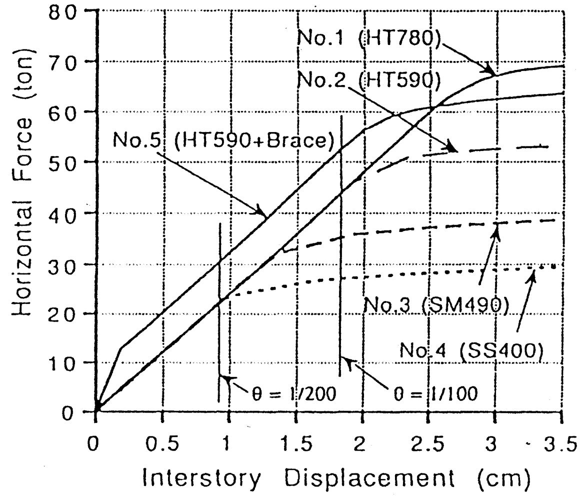


Fig. 7.4 Analysis Results of Horizontal Force vs. Inter Story Displacement

8. Conclusion

Seismic design has been studied for 30 years, allowing the plastic deformation of a main structure and expecting its energy absorption. This is because, for elastic design, the stiffness is relatively high and structural materials are not strong enough. Actually, the building whose seismic safety depends on its own plastic deformation would save people, but could not be used again after earthquakes. Consequently, it would lose its value of fortune.

This paper is based on the new concept "A building should be recovered even after large earthquakes.". We propose a new structure which consists of two independent structural systems, an elastic supporting system and a plastic seismic system. This system is one of the practical applications of Performance Based Design which emphasizes that "it is rational that one design requirement corresponds to one design parameter".

This structural method has become possible by the development of new materials: steel with high strength and large elastic strain, and steel with very low yield strength and large plastic deformability. A plastic seismic system requires a large plastic deformability, but an elastic supporting system is expected to have elastic behavior, and plastic deformability is not required and a higher yield point is preferable.

In this structural method, the elastic supporting system keeps its elasticity during earthquakes and the building can still be used again by replacing the plastic seismic system.

9. Acknowledgment

Helps of Dr. Takahiro Yamada, Mr. Kenichi Yoshida, Mrs. Masako Yoneda and Mr.. Alex V. Chachkes have been appreciated.

Appendix A. Unbond Brace

The unbond brace is a brace that has the steel core plate constrained by concrete filled steel pipe so that the core plate does not buckle.

A special isolating material that is called the unbond material, is used between the concrete and core plate to reduce friction, so that the steel pipe and concrete are not subjected to axial forces.

This combination allows the unbond brace to be used as an earthquake-resistant member that has stable hysteresis under both tensile and compressive forces. The stiffness and strength of a building can be adjusted to any desired value by the optimum selection of cross-sectional area and strength of core plate.

It is confirmed that the unbond brace exhibits stable hysteresis if the buckling strength of the steel pipe is higher than the yield strength of the core plate.

$$Py < \frac{\pi^2 EI}{L_k^2}$$

where Py is the yield strength of the core plate, I is the geometrical moment of inertia of the steel pipe, and Lk is the length of the unbond brace.

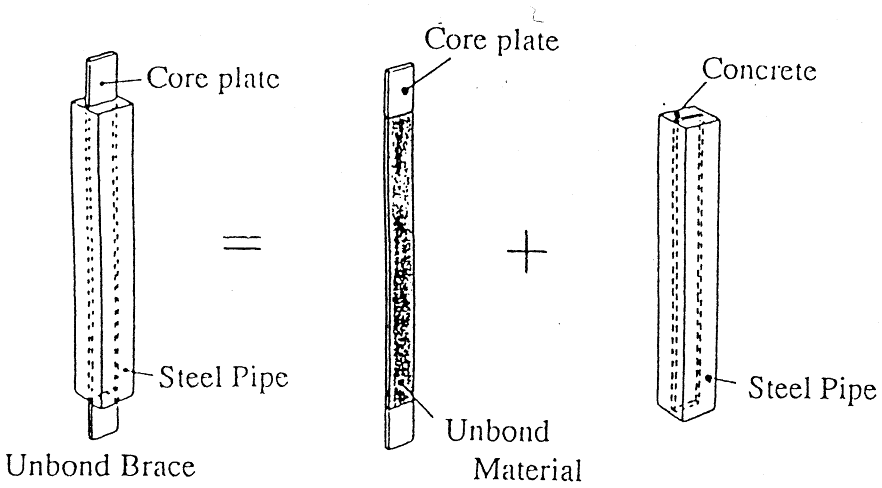
The features of the unbond brace are summarized as follows:

(1) Simply modeling in the structural analysis.

(2) Easy handling in the construction.

(3) Stable Hysteresis without buckling.

(4) Design flexibility in the stiffness and strength of a building.



Appendix B. I.K.Building

The I.K.Building is a seven-story office building under construction in Tokyo. We set two targets as follows:

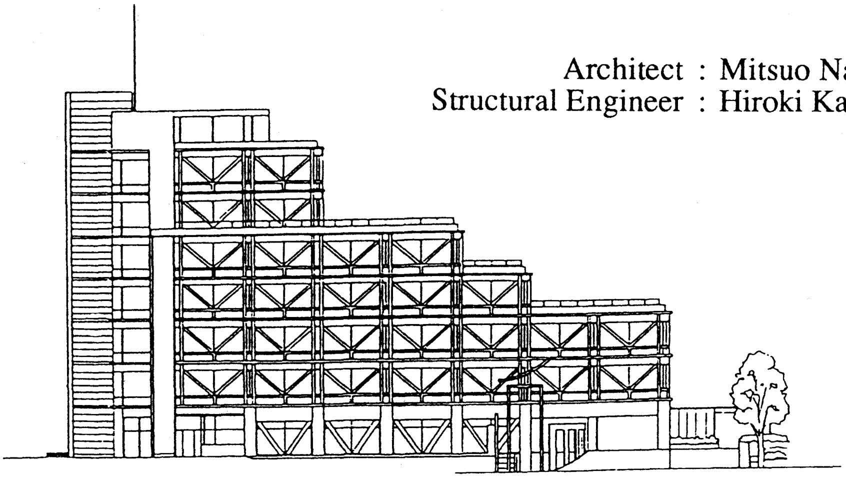
(1) No damage should be allowed in the main structure (columns and floors) that carries gravity load.

(2) The earthquake input energy should be entirely absorbed by the unbond braces.

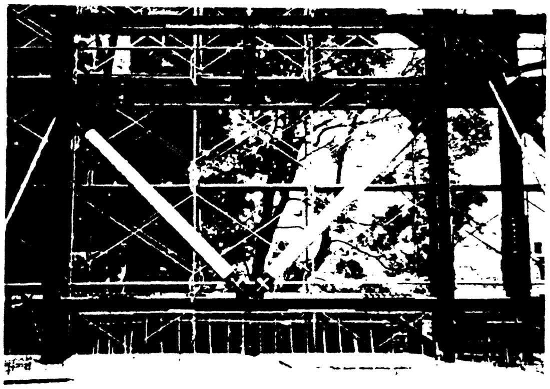
A flat slab structure and an unbond brace structure were adopted to meet the first and second targets, respectively. The flat slabs structure can carry the floor load of the building and can elastically deform against horizontal force, because the flat slab is low in stiffness. However, the flat slab structure alone cannot provide earthquake-resisting construction because of its low strength. The unbond braces are attached to the flat slab structure to gain enough stiffness, strength and ductility against earthquake.

When exposed to a large earthquake, the I. K. building will be only slightly damaged with cracks in the main structure (columns and floors), and only the unbond braces will plastically deform. This is an example of damage tolerant structure.

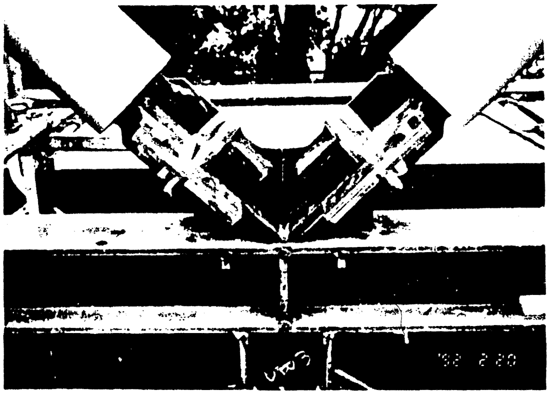
Architect : Mitsuo Nakamura
Structural Engineer : Hiroki Kawai



Elevation of I.K.Building



Unbond Brace installed to I.K.Building



Detail