A.I.J. LIMIT STATE DESIGN COMPETITION
DESIGN OF STEEL STRUCTURE BUILDING WITH HYSTERETIC DAMPER

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Abstract
In this paper the design of a 3-story office building located in Tokyo is discussed. The structure of the building is steel flame with histeretic damper, the design of which is based on the concept of seismic energy. In order to realize the design based on such latest study results, limit state design is adopted.
It is important that the structural designer communicates with clients and architects, analyzes the request of the client, and carries out cost studies, before deciding the structure type and performance grade. Such processes of design decision are also shown in details in this paper.
To carry out limit state design in practice, estimation variation is very important. Here 'variation estimation flow-chart' is proposed. This chart expresses the relation among various uncertain factors explicitly, therefore it will also express the recognition of structural engineers about such factors.

Introduction

To realize the performance oriented design, limit state design is said to be one of the most useful method. However strict limit state design is very complicated and many practical problems are left. In this paper, the advantages and the art of L.S.D. in practice are shown through the example of structural design for structural engineers using in practice.

Condition of Design

The building discussed here is a 3-story steel frame building located in Tokyo, a typical frame and plan of which is shown in Fig.1. The soil condition is ordinary and classified in type2 category in the AIJ design code. Clients' request for this project is summarized as follows. 1. can be used as a rental office, 2. Building life-time is at least 100 years, 3. Still serviceable against earthquakes occurred a few times for the life-time of the building, 4. most economic in terms of life cycle cost, 5. long span and without brace and walls outside
To clarify the performance of the building and to express the performance quantitatively, limit state design based on the reliability theory is adopted. Recently it is reported that the input seismic energy can be one of the valid index for the destructiveness of structures. To apply this concept to the design, limit state design is very useful.

L.R.F.D.

Load resistance factor design(LRFD) is adopted because of its easiness and simplicity. It is available to use existing calculation program for structural design. LRFD is expressed in form(1) assuming log-normal variables of load intensity(Q) and resistance(R)

$$\frac{1}{\sqrt{1+V_Q^{\,2}}}\exp\left(\alpha_Q\beta_T\sqrt{\ln\left(1+V_Q^{\,2}\right)}\right)\mu_Q \le \frac{1}{\sqrt{1+V_R^{\,2}}}\exp\left(-\alpha_R\beta_T\sqrt{\ln\left(1+V_R^{\,2}\right)}_R\right)\cdot\mu_R \qquad (1)$$

μ_Q, μ_R V_Q, V_R α_Q, α_R are mean and C.O.V. and separation factors of Q, R respectively. β_T is the target reliability index. In the practice of structural design there are many

factors which have variations. One of the merit of L.S.D. is to reflect such variations to the design as coefficients.

Seismic Performance Matrix

In Japan seismic risk can not be ignored, because of many earthquakes which sometimes bring about loss of property and fatalities. It is important for structural engineers to decide the concept of the seismic design and to account for the seismicity of the building to clients through the plain expression. To help structural engineers communicate with clients, seismic performance matrix below is proposed.

Table 1. Seismic performance matrix

	Earthquake load intensity level			
	Level 1	*Level 2*	*Level 3*	*Level 4*
Return period	30 years	100 years	500 years	1000 years
Ve (kine)	40	80	150	200
grade A				serviceable
grade B			serviceable	ultimate
grade C		serviceable	ultimate	
grade D	serviceable	ultimate		

Three limit states mentioned below can be assumed. When deciding limit states, characteristic of the building and clients' request must be taken into consideration. **Ultimate limit state:** Within this limit state, the building can be repaired and there will be no fatalities in the building. The structural criteria for this limit state is the story drift ratio of 1/100, which is determined by considering the strength of the PC wall fastener. **Serviceability limit state:** Within this limit state, the building can continue to be in use after the earthquake. The structural criteria for this limit state is that all members are elastic, and response acceleration is within 600gal, criteria of which is determined by considering seismicity of facilities. **Computer operation limit state:** Within this limit state, computers operate normally. Recently importance of computers is increasing and losses brought by computer error should not be neglected. That is why this limit state is proposed.

Table 2. Criteria for each limit state

	building	*facilities*
ultimate	drift of 1/100	
serviceable	members are elastic	600gal
computer		250gal

To make the image of earthquake clear, earthquake intensity is divided in 4 different levels. Level 1,Level 2 is determined by return period provided, which are 30 years and 100 years respectively. The process of determination is, 1. Maximum bedrock velocities are determined for each return period from statistic model of historical earthquake data of the location, 2. From the bedrock velocities, the target acceleration response spectrum for design is estimated, 3. Artificial earthquake wave is made to suit the target spectrum.

The earthquake of over 500 years return period is very rare, so the period in which historical earthquake data is recorded is not enough to estimate. For the level 3 and level 4, it is more rational to determine the value assuming fault model. Level 3 is the same level as Kanto Earthquake (1923). Level 4 is determined assuming the imaginary active fault, the parameters of which are the same level as Kobe Earthquake (1995).

Cost Study

There are many ways to decide the target optimum reliability. Here eq. (2) below is used, which will bring about the optimum target reliability index β_T based on minimizing total cost for given failure cost at ultimate limit state (Kanda and Ellingwood, 1991).

$$\beta_T = -\alpha_Q V_Q + \sqrt{(\alpha_Q V_Q)^2 + 2\ln\left(\frac{g}{\sqrt{2\pi}k\alpha_Q V_Q}\right)} \tag{2}$$

Here $k = 0.1$, $\alpha_Q = 0.85, V_Q = 0.6$. are used. Normalized failure cost g is 3.0 (3 times as initial construction cost), which is evaluated considering losses of rental office revenue and business interruption. For ordinary office building, the value of g is around 2.0. Considering importance of this building, g=3.0 is said to be adequate. Thus target reliability index β_T =2.0 is obtained from eq. (2).

Design Earthquake Load

From stochastic analysis of earthquake record data, seismic load is given as stochastic parameters assuming earthquake 50-year maximum surface acceleration log-normally distributed (Kanda and Ellingwood, 1991). Mean is 189gal and C.O.V. is 0.63. Parameters for the 100-year maximum value distribution should be estimated because the life-time of this building is 100 years. Cumulative distribution function of 100-year maximum value, $F_{100}(x)$, is obtained from equation using that of 50-year, $F_{50}(x)$.

$$F_{100}(x) = \{F_{50}(x)\}^2 \tag{3}$$

$F_{100}(x)$ in eq. (3) is no longer log-normally distributed. From the eq. (3) the 50-percentile value (x_{50}) and the 99-percentile value (x_{99}) are obtained. And from the simultaneous eq. (4), mean and C.O.V. of 100-year maximum distribution are obtained.

$$F_{100}(x_{99}) = 0.99 \quad \text{and} \quad F_{100}(x_{50}) = 0.50 \tag{4}$$

The relation between S_a (Response acceleration spectrum for design) and the value of the maximum acceleration is proposed in (AIJ, 1999). Further more the energy equivalent velocity (V_e) is also obtained from equation proposed in (AIJ, 1993a) for S_a above. Thus mean and C.O.V. of V_e are 93kine and 0.64. To achieve $\beta_T = 2.0$, the design value of V_e should be 200kine. Therefore the target performance of *grade B* in table1 is recommended for the structure.

Structural Design

To survive an epicentral earthquake such as Kobe Earthquake (1995), building's capacity of energy absorption must be larger than the input seismic energy (Hitoshi *et al.*, 1997). Here, hysteretic dampers are adopted and designed to absorb all seismic input energy. The reason is that it is difficult to estimate the capacity of energy absorption of the flame structure buildings. Histeretic dampers used here is made of low-yield-point steel, the F-values of which are 1.0. The process of damper design is as follows.

Symbol ΔE_{in} stands for the input seismic energy for half cycle at maximum amplification, which is estimated by next eq. (5)

$$\Delta E_{in} = \frac{1}{2} E_{in} \ , \qquad E_{in} = \frac{1}{2} M V_e^{\,2} \tag{5}$$

Symbol ΔE stands for the capacity of energy absorption of the histeretic damper. It corresponds to the area of half of histeretsis loop, which is estimated by eq. (6).

$$\Delta E = 2\sum \left(Q_P \left(\delta_{\max} - \delta_y \right) \right) \tag{6}$$

Q_P is the yield point of the steel shear panel, which is calculated by its size. $\delta_{\max}$ is maximum displacement and δ_y is estimated from Q_P and K_{eq}. K_{eq} is the equivalent stiffness of the damper-in column, and that is estimated from the static analysis of stress and displacement for the frame around the damper-in column.

The frame structure besides damper-in column is mainly designed for only fixed load, which are the live load and dead load. It is also designed to be elastic at ultimate limit state, where the drift ratio is 1/100.

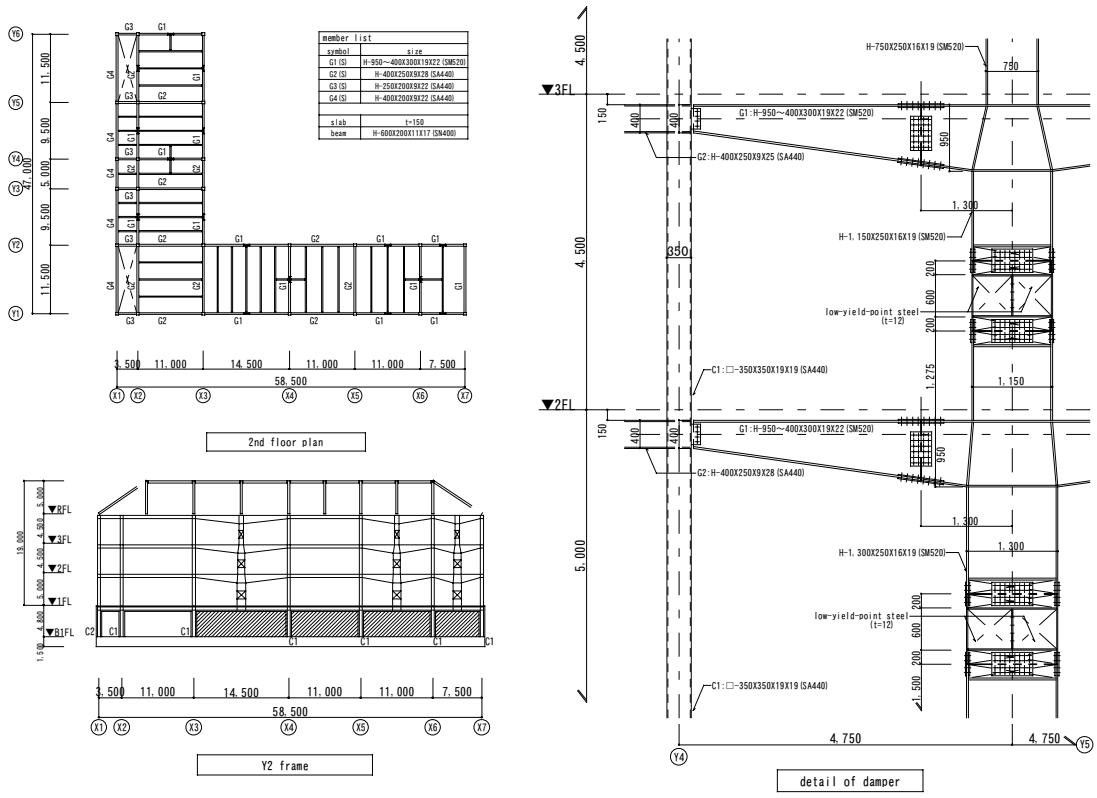
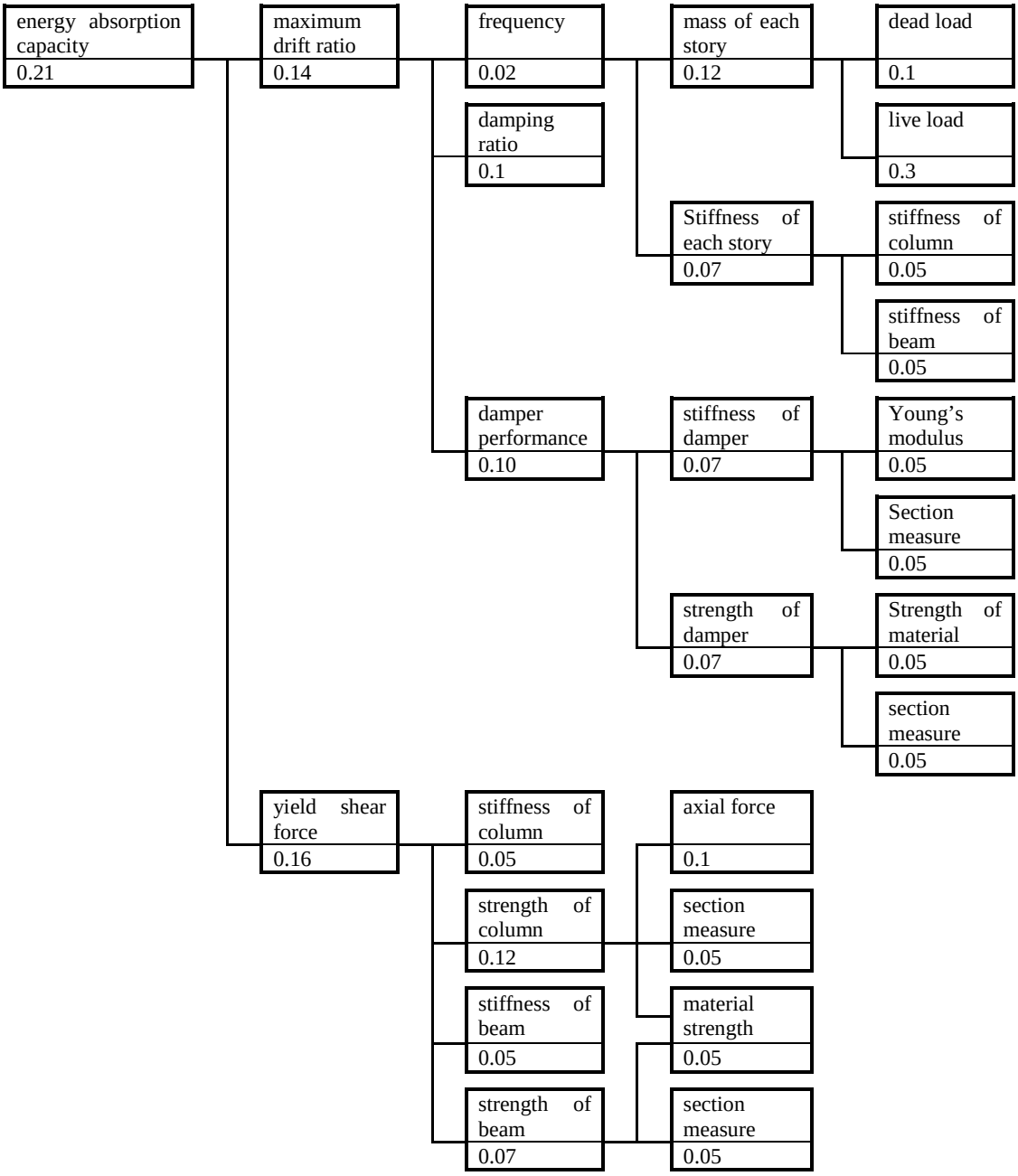


Figure 1. Plan and frame of the building and details of damper-in column

Variation Estimation Flow-chart

Here '*variation estimation flow-chart*' is proposed. Coefficient of variation (C.O.V.) is a very important factor in limit state design, therefore it should be decided by experimental data. But there are many cases where the C.O.V. are unknown and structural engineers must estimate those from known data. In such cases *variation estimation flow-chart* proposed below is very useful. This chart expresses the relation among various uncertain factors explicitly, so it will also express the recognition of structural designer about such factors. C.O.V. of seismic intensity in the previous chapter is also estimated by the same way as this chart.

Table 3. Variation estimation flow-chart



Confirmation of Adequateness

To confirm adequateness of the design, here the vibration analysis is carried out, in which an artificial earthquake wave referred to in previous chapter is used. Response drift ratio and response acceleration for each floor is shown in fig.3-1,3-2 respectively. As a result the seismic grade of this building is expressed as table3.

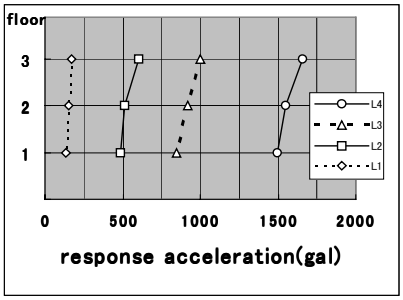


Fig. 3-1 response acceleration

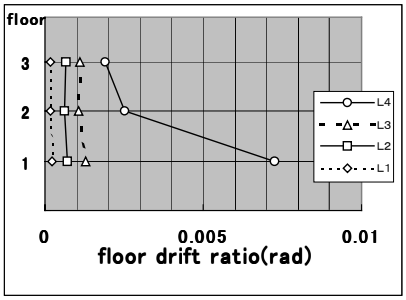


Fig.3-2 response floor drift ratio

Table 3. Seismic performance of this building

	Level 1	*Level 2*	*Level 3*	*Level 4*
building			serviceable	ultimate
facilities	computer	serviceable		

Conclusions

In order to apply the latest study result such as energy method and to clarify the seismic performance limit state design is adopted. The process of determining seismic performance through the cost study and argument with clients is shown in this paper. It is also shown that variation estimation flow-chart is useful in estimating variation of an integrated factor.

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