PERFORMANCE-BASED DESIGN FOR A SHEAR BUILDING SUBJECT TO DESIGN EARTHQUAKES WITH NON-MONOTONIC DISPLACEMENT SPECTRUM BY USING TIME HISTORY RESPONSE ANALYSIS

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ABSTRACT :

This paper proposes a stiffness design method for shear buildings subject to a design earthquake with a non-monotonic displacement spectrum. The objective function that is a combination of the fundamental natural period which represents 'cost' and the level of maximum displacements which represents 'performance' is introduced into the design method to find a set of story stiffnesses under response constraints. An inverse problem formulation is used to find the stiffness such that the shear building would exhibit maximum inter-story drifts proportional to specified ones. Several design examples and time history response analyses are performed to demonstrate the validity and the accuracy of the proposed design method.

KEYWORDS: Displacement-based Design, Non-monotonic, Time History Response Analysis

1. INTRODUCTION

Displacement response constrained stiffness design methods have already been established for shear structures subject to earthquake motions having a displacement response spectrum that increases monotonically as the natural period increases[1]. Methods for the inverse substitution of the story stiffnesses obtained from these methods into the framework structure have also been proposed[2],[5]. Further, the authors have already proposed a stiffness design method for shear structures subject to earthquake motions having a displacement response spectrum that increases non-monotonically with respect to the natural period, which is a more general case[3],[4]. In the above methods, the response spectrum method is adopted as the method of evaluating the response to the input earthquake motions, so when the design response range extends into the elastic plastic range, it is necessary to introduce equivalent linear methods.
In the equivalent linear methods, an elastic plastic structure is replaced with an equivalent elastic structure, so the maximum response can be evaluated without the use of elastic plastic time history response analysis, and this thinking can also be partially incorporated into the calculation of the limiting resistance. However, in order to carry out a high accuracy response evaluation, it is necessary to pay sufficient attention to the modeling of the restoring force characteristics and setting the equivalence conditions in applying the method. Also, to verify the accuracy, in any case it is necessary to carry out a comparison to an elastic plastic time history response analysis.
In the present research, the authors combine the method already proposed for performance-based stiffness design of shear structures[3] and a method of evaluating the maximum response by time history response analysis, and propose a method of obtaining the stiffness distribution that minimizes the value of a weighting function of "cost" represented by the fundamental natural period and "performance" represented by the inter-story displacement evaluated by time history response analysis.

2. DESIGN PROBLEM FOR DESIGN INPUT EARTHQUAKE MOTIONS HAVING A NON-MONOTONIC DISPLACEMENT RESPONSE SPECTRUM

2.1. Structure Model

An N story translational shear structure rigidly connected to the ground was adopted as the simplest structure model for constructing a performance-based stiffness design method. This structure model is hereafter referred to as the SB (Shear Building) model. The concentrated mass on the j^{th} floor and the floor stiffness of the SB model are represented by m_j and k_j respectively. The structure attenuation characteristics were the attenuation proportional to the initial stiffness, and a primary attenuation coefficient of 2%.

2.2 Stiffness Design Problem for Design Input Earthquake Motions Having a Non-monotonic Spectrum

The objective of actual structural design using dynamic analysis is to determine the size of each member in the framework model so that the inter-story drift angle or the story plasticity ratio are less than or equal to predetermined allowable values for several design input earthquake motions, but it is not a requirement to exactly equal the predetermined allowable values. Therefore, in performance-based design methods, if there is no solution in which the response exactly equals the allowable values, provided there are only solutions in which the response is less than the allowable values, the method of searching for the most desirable of these solutions has significance for actual design work.
In this paper, in order to construct a basic solution procedure of the performance based stiffness design method using a time history analysis method as the response evaluation method, firstly the story stiffness design problem is defined with the design input earthquake motion consisting only of a single mock earthquake motion or a single recorded earthquake wave. If the design input earthquake motions consist of several earthquake motions, then the method proposed in the next section may be applied. In that method the fundamental vibration component evaluation from the response spectrum method and the maximum inter-story displacement evaluation from the time history response analysis are repeated several times corresponding to the number of input earthquake motions. Then the envelope values for the fundamental vibration component and the maximum inter-story drift for each earthquake wave are obtained as "the fundamental vibration component for the design earthquake motion group" and "the maximum inter-story drift for the design earthquake motion group" respectively.

2.2.1. Story stiffness design problem

When the design input earthquake motions, the mass distribution at each story, and the structural attenuation characteristics are defined in the SB model in advance, the story stiffness distribution $\{ k_j \}$ is determined so that following conditions are all satisfied,

$$T_L \leqq T^{(1)} \leqq T_U \tag{2.1}$$

$$\delta_{j\max} = \alpha \, \bar{\delta}_j \quad (j=1,\cdots,N) \tag{2.2}$$

$$\alpha \leqq 1 \tag{2.3}$$

$$\beta = 1 - T^{(1)} / T_U \tag{2.4}$$

and the objective function

$$f = \gamma_1 \alpha + \gamma_2 \beta \quad (\gamma_1 + \gamma_2 = 1) \tag{2.5}$$

is minimized, where γ_1 and γ_2 are positive.
Here T_L and T_U are the lower bound and upper bound values of the fundamental natural period $T^{(1)}$ respectively, γ_1 is the weighting coefficient of the inter-story drift, γ_2 is the weighting coefficient of the fundamental period, and $\delta_{j\max}$ is the maximum inter-story drift of the j^{th} story for the design earthquake motions, as evaluated by the time history response analysis. $\bar{\delta}_j$ is the j^{th} story component of the shape that specifies the inter-story drift distribution. In the above stiffness design problem, the smaller the value of α, the smaller the inter-story drift in the SB model, so α is a parameter that represents the "performance" of the structure. On the other hand, the smaller the value of β, the longer the fundamental period of the SB model, so β is a parameter that represents the "cost" of the structure. Therefore, γ_1 is a weighting coefficient with respect to the performance index, γ_2 is a weighting coefficient with respect to the cost index, and designers determines the values of γ_1 and γ_2 depending on their emphasis on performance or cost.

2.3 Method of Solving the Story Stiffness Design Problem

The above story stiffness design problem can be solved by the following analysis method, using the predominance of the fundamental vibration in the elastic response of a high rise building during an earthquake and the similarity between the elastic response and the elastic plastic response when excessive concentration of deformation does not occur.
[Step 0] It is assumed that all the maximum inter-story drifts $\delta_{j\max}$ are accounted for by the fundamental vibration components $\delta_j^{(1)}$, or $\bar{\delta}_j^{(1)} = \bar{\delta}_j$. Here, $\delta_j^{(1)}$ is evaluated by the response spectrum method taking the first mode only into account, and assuming the response is within the elastic range. [Step 1] The story stiffness distribution that satisfies the condition Eqns. 2.1, 2.3, 2.4, and the following equation,

$$\delta_j^{(1)} = \alpha\bar{\delta}_j^{(1)} \tag{2.6}$$

and minimizes the objective function 2.5 is derived by a method[3] that combines the inverse problem formulation[1] and optimization theory. [Step 2] Time history response analysis is carried out, to calculate the maximum inter-story drift distribution of the SB model. [Step 3] Check whether Eqn. 2.2 is satisfied to within a certain accuracy or not. If satisfied, it is considered that Eqn. 2.2 is satisfied in the SB model, and the routine terminates. If not satisfied within a certain accuracy, the fundamental vibration component is modified in accordance with the following equation,

$$\bar{\delta}^{(1)}_{j\,\mathrm{updated}} = (\bar{\delta}_j^{(1)} / \delta_{j\max})\bar{\delta}_j \tag{2.7}$$

and the routine returns to Step 1 with $\bar{\delta}_j^{(1)} = \delta^{(1)}_{j\,\mathrm{updated}}$.

3. **EXAMPLE**

The Taft 1952 EW with a maximum ground velocity amplitude of 50cm/s was adopted as an example of design input earthquake motion. Figure 1 shows the displacement response spectrum (attenuation constant 2%) for a maximum velocity amplitude of 50cm/s. Also, Figure 2 shows the acceleration time history wave form for the design input earthquake motion. In the present example, the story restoring force characteristics of the SB model are assumed to be normal bi-linear, the yield displacement of the j^{th} story is expressed by δ_{yj}, and the second branch stiffness ratio of the j^{th} story is expressed by κ_j .

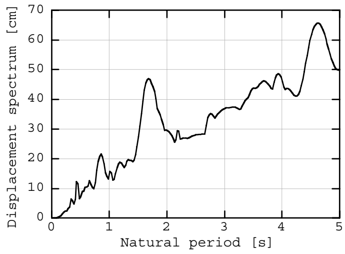


Figure 1 Displacement spectrum (h=2%)

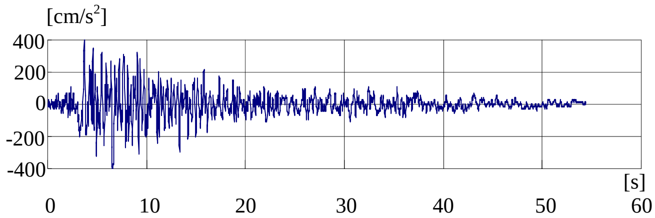


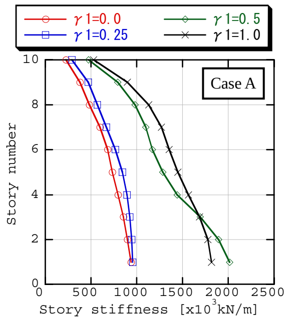
Figure 2 Accelerogram of Taft 1952 EW earthquake motion

3.1 Example 1: 10 story model

The common parameters were as follows: m_j=980ton, $\bar{\delta}_j$=4.0cm (in Case D only restricted to a trapezoidal shape in the upper and lower storys), T_L=0.8s, and T_U=1.8s. There were four cases for the weighting parameter γ_1 of the objective function: 0.0 (greatest emphasis on the cost index), 0.25, 0.5, and 1.0 (greatest emphasis on the performance index).

3.1.1 Case A: Elastic design

It was assumed that the response was within the elastic range, with κ_j = 1.0. Figure 3 shows the story stiffness distribution obtained, and Figure 4 shows the maximum inter-story drift distribution.



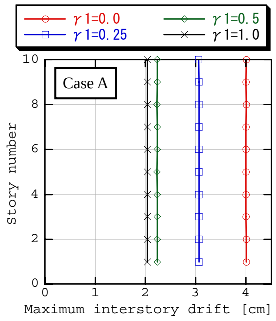
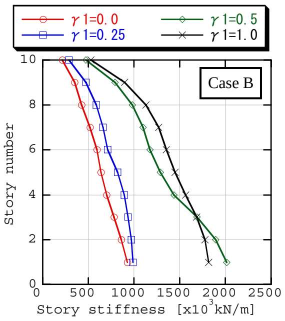


Figure 3 Distributions of story stiffness Figure 4 Distributions of interstory drift

It can be seen that even though the shape of the inter-story drift distribution is the same, the magnitude varies with γ_1, so the shape of the story stiffness distribution varies accordingly. This is one of the characteristics that can be seen when an earthquake motion having non-monotonic response spectrum characteristics with respect to the natural period is used as the design input earthquake motion[3],[4].

3.1.2 Case B: The case where δ_{yj} = 2.2cm, κ_j = 0.6

Figure 5 shows the story stiffness distribution obtained, and Figure 6 shows the maximum inter-story drift distribution.



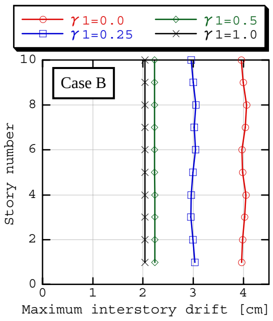


Figure 5 Distributions of story stiffness Figure 6 Distributions of interstory drift

In the cases with γ_1= 0.0 and γ_1=0.25, the maximum inter-story drift distribution is virtually the same in both cases as for the elastic design, but a slight difference in the story stiffness distribution can be seen, the stiffness being somewhat smaller in design when plasticity is allowed. With γ_1 = 0.5, the response only very slightly exceeded the elastic limit (2.2cm), so the structure was almost completely within the elastic range, and the story stiffness distribution was virtually the same as for the elastic design case. Figure 7 shows the time history of story shear force – inter-story drift for the 1st and 10th floors, for the γ_1= 0.0 design.

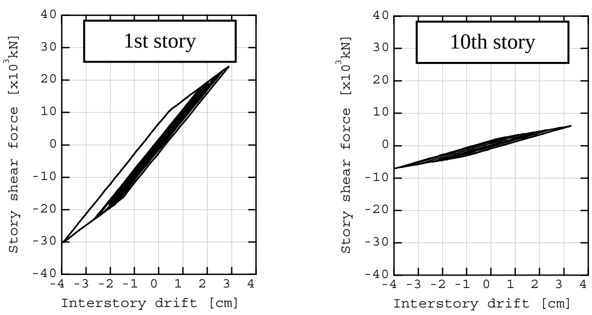


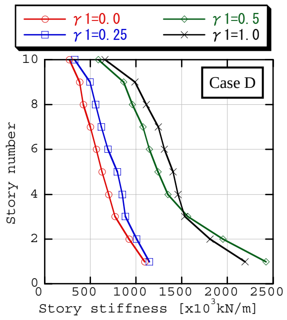
Figure 7 Story shear force-inter-story drift relationships at γ_1 =0.0

3.1.3 Case C: The case where δ_{yj} = 2.2cm, κ_j = 0.4

Although a solution was obtained for the cases with γ_1= 0.5 and γ_1=1.0, for the cases with γ_1= 0.0 and γ_1= 0.25 the solution oscillated in the design change process with the solution method described in section 2.3, so a solution was not obtained. What this means is that even if a design is obtained in which with the restoration force characteristics as in the present example, the response is in an area with the stiffness ratio after yielding at a specific value, and the response changes greatly due to small changes in the story stiffness and the inter-story drift, etc.

3.1.4 Case D: Trapezoidal shaped $\bar{\delta}_j$, δ_{yj} = 2.2cm, κ_j = 0.6 (δ_{yj} and κ_j are the same as in Case B)

Figure 8 shows the obtained story stiffness distribution, and Figure 9 shows the maximum inter-story drift distribution.



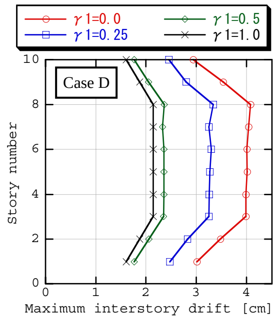
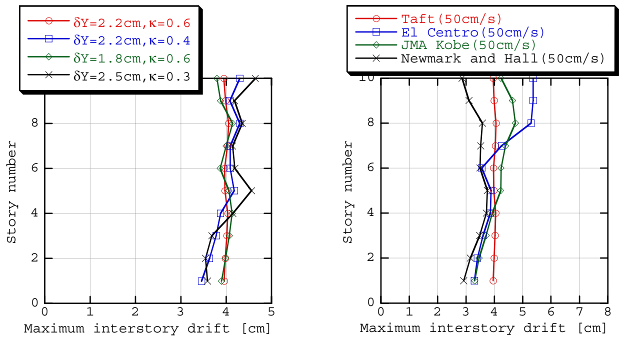


Figure 8 Distributions of story stiffness   Figure 9 Distributions of interstory drift

3.1.5 Change in maximum response for changes in parameters

Change in restoring force characteristics: The change in the maximum inter-story drift was investigated for the design in Case B with $\gamma_1 = 0.0$, when δ_{yj} and κ_j were changed. Figure 10(a) shows the results. When only the yield displacement δ_{yj} was changed, there was no distinct change in the maximum response. In contrast, when the second branch stiffness ratio κ_j was changed to be smaller, it was observed that the shape of the maximum response distribution changed greatly.

Changes in the design input earthquake motion: Mock earthquake motions (10 waves) compatible with the El Centro 1940 NS (maximum velocity amplitude 50cm/s), JMA Kobe 1995 NS (maximum velocity amplitude 50cm/s), and Newmark and Hall Design Spectrum[6] (maximum velocity amplitude 50cm/s) were applied to the design in Case B with $\gamma_1 = 0.0$, and the maximum inter-story drift was calculated. The results are shown in Figure 10(b). However, the results for the mock earthquake motions that apply the Newmark and Hall design spectrum are shown as average maximum values (average value of the maximum values). It is necessary to be aware that when the input earthquake motion is varied, the distribution of the inter-story drift deviates from the target distribution during design, due to the concentration of deformation as a result of plasticity.



(a)   (b)

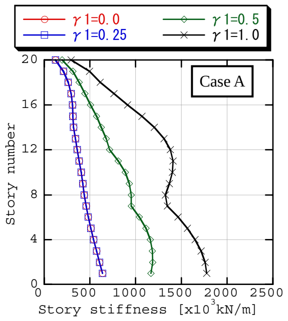
Figure 10 Variations of maximum inter-story drift

3.2 Example 2: 20 story model

The common parameters were as follows: $m_j = 980$ton, $\bar{\delta}_j = 4.0$cm (in Case C $\bar{\delta}_j = 3.0$cm in the upper half of stories), $T_L = 1.8$s, $T_U = 3.8$s. There were four cases for the weighting parameter γ_1 of the objective function: 0.0 (greatest emphasis on the cost index), 0.25, 0.5, 1.0 (greatest emphasis on the performance index).

3.2.1 Case A: Elastic design

Figure 11 shows the story stiffness distribution obtained, and Figure 12 shows the maximum inter-story drift distribution.



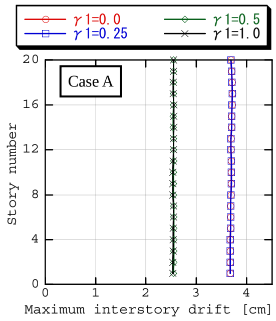
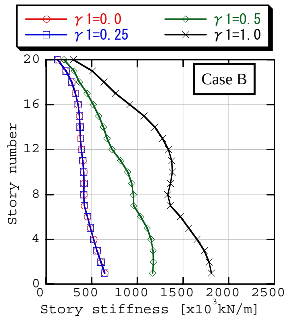


Figure 11 Distributions of story stiffness   Figure 12 Distributions of inter-story drift

The designs in the two cases with $\gamma_1 = 0.0$ and $\gamma_1 = 0.25$ were exactly the same. Also, there was quite a large difference in the story stiffness distributions for the two cases $\gamma_1 = 0.5$ and $\gamma_1 = 1.0$, but the maximum inter-story drift distributions were virtually the same. In this way it can be seen that it is a characteristic when using earthquake motions having a non-monotonic response spectrum with respect to the natural period as the design input earthquake motion that the same stiffness design may be obtained even if the weighting of the performance index and the cost index are changed, or a stiffness design is obtained for which there is a large difference in the cost index but almost no change in the performance index. In the design with $\gamma_1 = 0.5$ the fundamental natural period was 2.660s, and in the design with $\gamma_1 = 1.0$ the fundamental natural period was 2.135s.

3.2.2 Case B: The case with $\delta_{yj} = 2.2cm$, $\kappa_j = 0.6$

Figure 13 shows the story stiffness distribution obtained, and Figure 14 shows the maximum inter-story drift distribution.



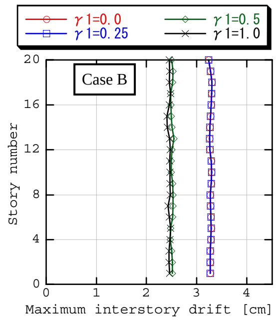
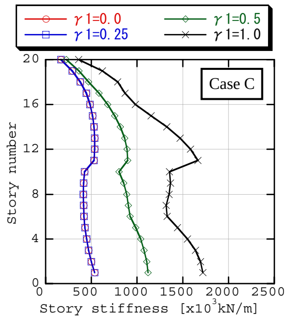


Figure 13 Distributions of story stiffness   Figure 14 Distributions of interstory drift

Comparing the two cases $\gamma_1 = 0.0$ and $\gamma_1 = 0.25$ with the elastic design, the story stiffnesses were virtually the same, but the inter-story drifts were smaller where plasticity was allowed, the same as in the 10 story model in Example 1.

3.2.3 Case C: The case with $\delta_{yj} = 2.2cm$, $\kappa_j = 0.6$, and in the top half of stories $\bar{\delta}_j = 3.0cm$

Figure 15 shows the story stiffness distribution obtained, and Figure 16 shows the maximum inter-story drifts. Even when the specified inter-story drift distribution suddenly changes at the boundary of a certain story, as in the present numerical example, it is possible to obtain a story stiffness distribution with an inter-story drift distribution proportional to a specified distribution, using the stiffness design method proposed in this research.



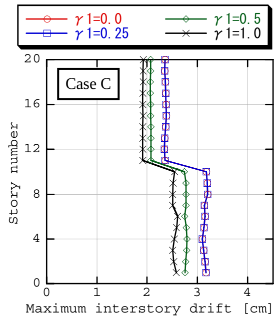


Figure 15 Distributions of story stiffness Figure 16 Distributions of inter-story drift

4. CONCLUSIONS

In the present research, a method is proposed for efficiently determining the stiffness distribution of a shear structure model subject to design input earthquake motions that minimizes the value of a function weighted for “cost” as represented by fundamental natural period and “performance” as represented by the inter-story drift evaluated from time history response analysis, by using inverse problem formulation and the predominance of the fundamental natural vibration in the earthquake elastic response. The proposed method is capable of obtaining a solution that satisfies the constraint conditions with sufficient accuracy for virtually any case where the response is within the elastic range.
The stiffness design method proposed in this paper allows a designer to easily produce several story stiffness distributions with a different balance between cost and performance. The designer can make an overall judgment and select the best story stiffness distribution from among the various distributions. Therefore it is concluded that the story stiffness design method proposed in this paper has sufficient significance for actual structural design work.

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