DIRECT INELASTIC EARTHQUAKE DESIGN OF R/C STRUCTURE

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ABSTRACT

A new earthquake design method performing iterative calculations with secant stiffness was developed. Since basically the proposed design method uses linear analysis, it is convenient and stable in numerical analysis. At the same time, the proposed design method can accurately estimate the inelastic strength and ductility demands of the structural members through iterative calculations. In the present study, the procedure of the proposed design method was established, and a computer program incorporating the proposed method was developed. The proposed method, as an integrated analysis and design method, can directly address the earthquake design strategy intended by the engineer, such as limited ductility of member and the concept of strong column - weak beam. Through iterative calculations on a structural model with member sizes preliminarily assumed, the strength and ductility demands of each member can be determined so as to satisfy the given design strategy. As the result, structural safety and economical design can be achieved.

1. Introduction

The equivalent static analysis/design method using linear elastic analysis and the response modification factor, which is the traditional earthquake design method, has serious disadvantages though it can be used conveniently in analysis and design. Although buildings of the same structural type frequently show different responses depending on their capacities of strength and ductility, the equivalent static method uses a common response modification factor. And the equivalent static method cannot accurately estimate the inelastic strength and deformation of each member because it uses linear elastic analysis.

Recently, to overcome the disadvantages of the equivalent static method, a variety of earthquake analysis/design methods using nonlinear static analysis were developed; the Capacity Spectrum Method (CSM, ATC 1996) and the Direct Displacement-Based Design Method (DDBD, Priestley 2000). Unlike the conventional equivalent static method, the nonlinear static methods can estimate the inelastic seismic performance of structures, and as the result, the structural safety can be secured against an earthquake. However, the existing nonlinear static methods still have several disadvantages in application.

The CSM can be applied only if the analytical model describing the nonlinear behavior of each member has been established. This means that the CSM can be used to evaluate the seismic performance of existing structures or the structures already designed, but cannot be used as a direct design method to determine directly the strength and ductility demand. Therefore, this method has difficulty in directly addressing the earthquake design strategy intended by the structural engineer. Inconveniently, after the structure is designed arbitrarily, repeated evaluation and redesign on the structure are required to secure its structural safety and economical design.

The DDBD simplifies an actual complex structure to a substitute structure of single degree-of-freedom. The DDBD can determine the strength and ductility demand for the substitute structure. However, it has difficulty in determining the strength and ductility of each member consisting of the actual structure from those of the substitute structure. This is because a variety of actual structures with different local demands can be represented

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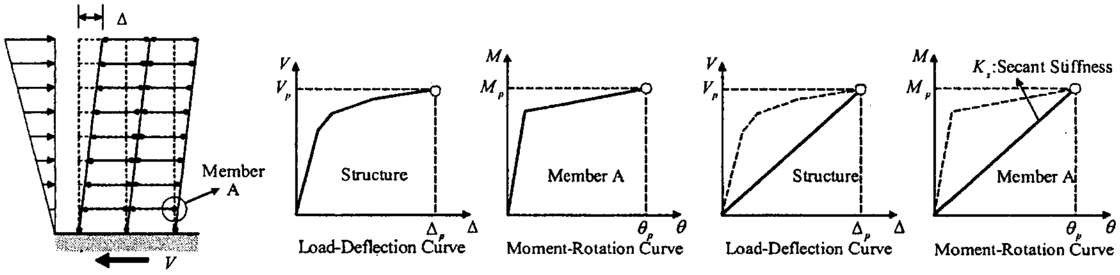
** Graduate Student, Dept. of Archt., Seoul National University by the same substitute structure. Therefore, practically, DDBD is applicable to low-rise buildings and bridges, which have a complete plastic failure mechanism, in a high-seismic zone. It is not appropriate for buildings in a low-seismic zone and for high-rise buildings with limited ductility demand instead of a complete plastic mechanism.

Due to such technical disadvantages, application of the existing nonlinear static methods is limited, and the equivalent static method is still popular regardless of its technical inaccuracy. The purpose of the present study is to develop a new earthquake analysis/design method that can overcome the disadvantages of the existing methods: As a direct earthquake design method, the proposed method can directly determine the strength and ductility required in each member. Furthermore, it is applicable to structures with various seismic performances including structures with a limited ductility demand.

2. Basic Design Concept

The basic concept of the earthquake design method proposed in the present study is to calculate the strength and ductility demands of structures and members resulting from their inelastic behavior by performing linear analysis for secant stiffness instead of the traditional nonlinear analysis. Fig. 1 (a) shows the deformed shape of a structure, and Fig. 1 (b) shows the load-deflection curve and the moment-curvature curve at a plastic hinge of a member. Figure (b) shows the global and local performance points defined with strength and maximum deformation resulting from the inelastic behavior of the structure and the member. Here, as shown in Fig. 1 (c), the same performance point can be obtained by carrying out a linear analysis for the secant stiffness corresponding to the performance point. This is possible because if the profile of the earthquake load does not change, only one strength exists for the same deformation even though the loading paths may be different. For this principle to be valid, the profile of earthquake load should not change during inelastic behavior, and each member should not be unloaded. These assumptions are generally accepted in the conventional nonlinear static methods.



(a) Deformed shape (b) Nonlinear analysis (c) Elastic analysis using secant stiffness

Fig. 1 Nonlinear static analysis vs. equivalent elastic analysis using secant stiffness

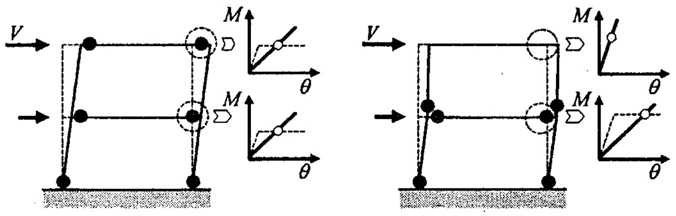


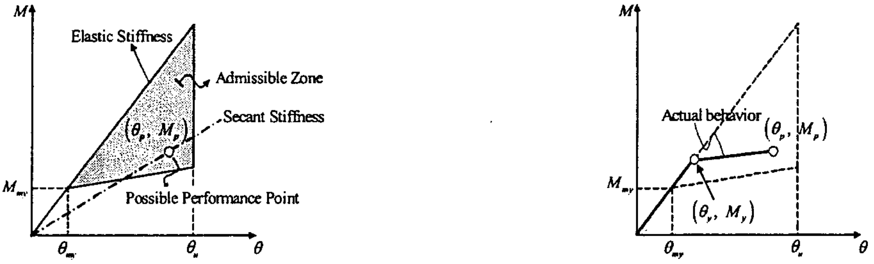
Fig. 2 Various Design Alternatives for the Same Earthquake Load

Conversely, if an arbitrary secant stiffness is used at each plastic hinge of the members and linear analysis using the secant stiffness is performed for a given earthquake load, a performance point can be calculated. If each member is designed so that its inelastic behavior passes the local performance point of the member, the same performance point can be obtained from the conventional nonlinear static analysis using inelastic member model. This result means that the linear analysis using the secant stiffness has the same effect as the conventional nonlinear analysis.

If the performance point is fixed to a specific value, as is done when the seismic performance of existing structures is evaluated, the linear analysis using arbitrary secant stiffness cannot obtain the same performance point as the nonlinear analysis does. However, when a new structure is designed, as shown in Fig. 2, a variety of the performance points for a given earthquake load can be selected according to the design strategy intended by the engineer. Therefore, a performance point can be determined by performing the linear analysis for an arbitrary secant stiffness. As mentioned, if each member is designed so as to satisfy the strength and deformation demands calculated by the linear analysis using the secant stiffness, the performance point resulting from the conventional nonlinear analysis is the same as that determined by the linear analysis. This result indicates that in structural designs, a performance point and the related strength and deformation demands of each member can be determined by linear analysis for secant stiffness.

Though basically the secant stiffness can be assumed arbitrarily in a structural design, the secant stiffness at the plastic hinge of each member should be appropriately selected to secure structural safety and economical design. For the purpose, the boundary of allowable secant stiffness must be established. Fig. 3 shows the admissible zone of the performance point (θ_p, M_p), and the secant stiffness that can be accepted generally. The conditions for the admissible zone are as follows.

1) The secant stiffness should be less than the elastic stiffness.
2) The strength required to resist earthquake load should be not less than that required for gravity load.
3) A member designed with seismic details according to current earthquake design provisions has a specific deformability θ_u. Therefore, deformation of each member at the performance point should be less than its deformability.



(a) Admissible zone for performance point (b) Actual behavior of the member corresponding to the performance point

Fig. 3 Determination of inelastic strength and deformation of the member using secant stiffness

The shaded area in Fig. 3 (a) indicates the admissible zone where the performance point can exist. In the preliminary analysis of a structure, the arbitrary secant stiffness is tried because it is not known if the performance point of each member belongs to the admissible zone. As the result of the analysis, if the performance point resulting from the analysis does not belong to the admissible zone, the secant stiffness is modified, and the analyses are repeated until at all the plastic hinges the performance points belong to the admissible zone. When the performance point of a member is determined as shown in Fig. 3 (a), the actual inelastic behavior of the member will be as shown in Fig. 3(b).

The boundaries representing the allowable minimum strength and maximum deformation can be established arbitrarily according to the earthquake design strategy intended by the engineer. For example, if the concept of strong column ? weak beam is intended to be introduced, development of plastic hinges in the column members should be restrained by increasing the boundary of the lowest strength. Also, if the detail of lateral confinement for ductility cannot be used, deformation of the plastic hinge can be restrained by decreasing the boundary of the maximum deformation. As such, if the strategy of earthquake design intended by the engineer is applied to establish the admissible zone, the performance point can be determined so as to satisfy the design concept.

3. Procedure of Direct Inelastic Earthquake Design

The procedure of the Direct Inelastic Earthquake Design (DIED) proposed in the present study can be summarized as follows:

1) After assuming sizes of the members, perform linear analysis for the gravity load, and establish the boundary of the minimum strength at each member. Here, the boundary of the minimum strength can be determined by the strategy of earthquake design such as the minimum flexural strength specified in the current design provisions, as well as by the gravity load.
2) Specify the maximum rotation at potential plastic hinges of each member, according to the ductility detail applied. Refer to either existing design provisions and manuals such as FEMA-273(BSSL, 1997) or experimental results.
3) Model the potential plastic hinges of each member. Generally, locate the potential plastic hinges at both ends of the member. If a conventional computer program for linear elastic analysis is used, the plastic hinges can be modeled as elements separate from the main element. In the element of plastic hinge, secant stiffness is used to present the inelastic behavior (Fig. 4).

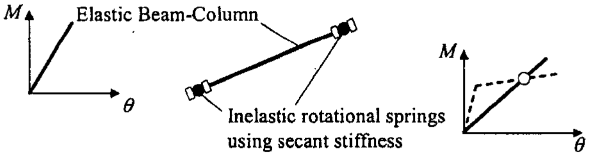


Fig. 4 Beam-column element with plastic hinges at both ends

4) Assume a secant stiffness at each potential plastic hinge. The secant stiffness should be less than the elastic stiffness K_e and greater than the minimum stiffness K_u corresponding to the boundary of the maximum rotation θ_u (Fig. 5). Here, K_e and K_u are calculated as

$$K_e = \frac{M_{my}}{\theta_{my}} \text{ and } K_u = \frac{M_{mu}}{\theta_u} \tag{1}$$

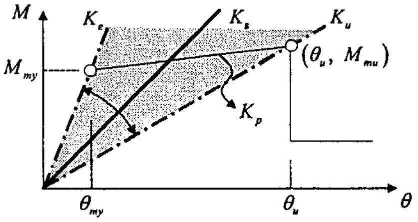


Fig. 5 Admissible range of secant stiffness

where θ_{my} = yield rotation, θ_u= maximum rotation, M_{my}= minimum moment corresponding to the yield rotation, and M_u= minimum moment corresponding to the maximum rotation. According to Priestley (2000), θ_y (= θ_{my}) can be approximately estimated, regardless of the amount of reinforcement.

$$\theta_y = \left(\alpha_{ST}\frac{\varepsilon_y}{h}\right)\left(\frac{h}{2}\right) = \frac{1}{2}\alpha_{ST}\varepsilon_y \tag{2}$$

where h = depth of member, ε_y = yield strain of longitudinal re-bars, α_{ST} = modification factor according to member type and shape of cross-section: α_{ST}= 2.35 for columns with rectangular section, 2.12 for columns with round section, 2.00 for walls with rectangular cross-section, and 1.70 for beams.

5) Calculate the earthquake load in accordance with the earthquake design code. Perform linear analysis using the assumed secant stiffness for the earthquake load.
6) If, at each plastic hinge, the local performance point does not belong to the admissible zone, the secant stiffness is modified. Though the secant stiffness can be modified arbitrarily, the following method was proposed in the present study.

As shown in Fig. 6, the secant stiffness is modified for the four cases classified by the locations of the performance point:

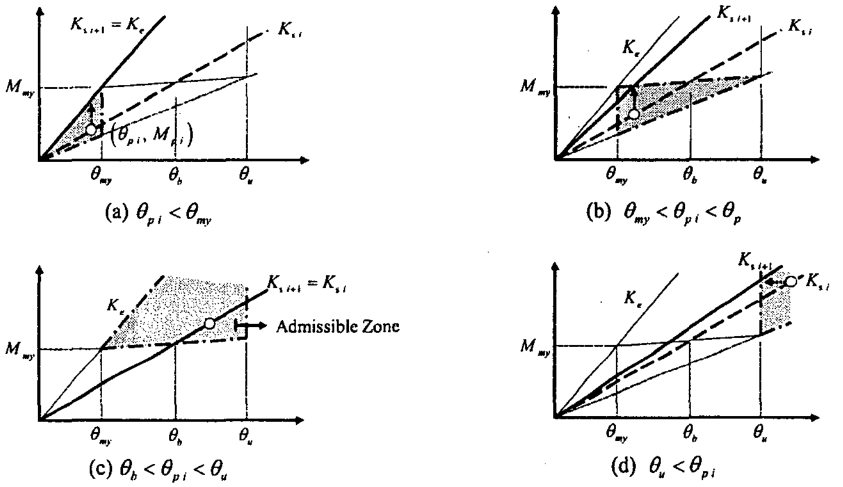
$$\text{For } \theta_{pi} < \theta_{my}, \quad K_{s\,i+1} = K_e \tag{3a}$$

$$\text{For } \theta_{my} \le \theta_{pi} \le \theta_u \text{ and } M_{pi} < M_{my} + K_p(\theta_{pi} - \theta_{my}), \quad K_{s\,i+1} = \frac{M_{my} + K_p(\theta_{pi} - \theta_{my})}{\theta_{pi}} \tag{3b}$$

$$\text{For } \theta_{my} \le \theta_{pi} \le \theta_u \text{ and } M_{pi} \ge M_{my} + K_p(\theta_{pi} - \theta_{my}), \quad K_{s\,i+1} = K_{si} \tag{3c}$$

$$\text{For } \theta_{pi} > \theta_u, \quad K_{s\,i+1} = \frac{M_{pi}}{\theta_u} \tag{3d}$$

At each plastic hinge, θ_{pi} = current rotation, M_{pi} = current moment, K_{si}, K_{si+1} = secant stiffness, and K_p= stiffness of the boundary of the minimum moment.



(a) $\theta_{pi} < \theta_{my}$

(b) $\theta_{my} < \theta_{pi} < \theta_p$

(c) $\theta_b < \theta_{pi} < \theta_u$

(d) $\theta_u < \theta_{pi}$

Fig. 6 Strategy for Modifying Secant Stiffness at Plastic Hinge

7) Repeat the analysis using the modified secant stiffness until the performance points belong to the admissible zone at all the plastic hinges.
8) If the structure is designed for more than two load patterns, the Direct Inelastic EQ Design is performed for a load pattern. Next, defining the strength resulting from the analysis as the minimum strength for each member, the Direct Inelastic EQ Design is performed for the other load patterns.

9) If the structure is designed for dual criteria such as serviceability and strength, firstly, the Direct Inelastic EQ Design is performed for the serviceability criterion. Next, defining the strength resulting from the analysis as the minimum strength for each member, the Direct Inelastic EQ Design is performed to satisfy the strength criterion.
10) Perform the strength and ductility design so as to satisfy the demands resulting from the analysis.

4. SUMMARY AND CONCLUSIONS

In the present study, a new earthquake design method, which can be used as a direct design method, was developed. The proposed method (Direct Inelastic Earthquake Design) uses a new numerical method performing iterative calculations for secant stiffness, and it can directly determine the inelastic strength and deformation demands with only the member sizes and load conditions used in the conventional elastic analysis. The proposed method uses a simple algorithm so it is convenient to use in numerical calculations. At the same time, it can analyze the inelastic behavior of structure through iterative calculations. In the present study, the procedure of the proposed method was established, and a computer program performing integrated analysis and design was developed. The advantages of the proposed method can be summarized as

1) The proposed method can directly calculate the inelastic strength and deformation demands with only the member sizes and load conditions.
2) The proposed method is applicable to structures with limited ductility demand such as high-rise buildings and buildings in low and moderate seismic zones.
3) The proposed method can directly address the design strategy intended by the engineers such as limited ductility of a member and the concept of strong column-weak beam.
4) Earthquake design based on member ductility is possible. As the result, the soft-story can be prevented and energy dissipation can be maximized by spreading the plastic hinges along the building height.
5) Since the inelastic numerical method using secant stiffness is versatile in application, it is applicable to existing earthquake design methods using elastic or inelastic analysis.

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