A Non-Iterative Direct Displacement-Based Design Procedure for Steel Bridges: Using Inelastic Design Spectrum

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ABSTRACT

Traditionally, in order to obtain the yield displacement of a nonlinear structure, the direct displacement-based seismic design method always requires a repeatedly iterative procedure no matter the equivalent linear systems (substitute structure) or inelastic design spectra was used in the procedure. That will sometimes result in inefficiency if several iterative cycles need to be produced in a design case for convergency. To avoid the disadvantage, this paper presents a non-iterative direct displacement-based design procedure for steel bridges, which uses the well-known Newmark and Hall inelastic design spectra to estimate the force and the displacement responses of nonlinear systems. Furthermore, when producing the proposed design method, no any linear or nonlinear analysis programs are needed.

Key Words : non-iterative, direct displacement-based design, inelastic design spectra

非迭代性直接位移設計法應用於鋼橋之設計：採用非彈性設計反應譜

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摘要

傳統上，直接位移設計法應用在非線性結構時，為了計算降服位移量，不論是採用等效線性系統（替代結構）法或是非彈性設計反應譜法兩種方法。經常必須進行反覆的迭代過程。因而經常造成收斂過程中，相當沒有效率的反覆迭代過程。為了避免這項缺點，本文提出一個非迭代性的直接位移設計法，並應用於鋼橋的設計中。上述方法採用了 Newmark and Hall 的非彈性設計反應譜去估計力量與位移的大小。本文提出的方法，不需採用任何分析程式即可完成。

關鍵字：非迭代、直接位移設計法、非彈性設計反應譜

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I. INTRODUCTION

Emphases in performance-based seismic design of structures are that the structural responses can reliably be met for a selected performance objective. To correspond to this purpose, it is important to develop a simple and effective method for designing and analyzing the design of structures. Based on the need, simplified nonlinear static analysis procedures, capacity spectrum method and coefficient method, have been incorporated in the ATC-40 and FEMA-273 (ATC, 1996 [1]; FEMA, 1997 [2]) for evaluation and rehabilitation of buildings. Differently, the methodology of direct displacement-based seismic design was developed to design new constructions and in which procedure only the static linear analysis was needed. The seismic design of structures using the direct displacement-based procedure can be carried out from a specified target displacement. It is interesting to note that the strength and stiffness are not the design variables in the procedure. Instead, they are the end results.

The fountainhead of the direct displacement-based seismic design methodology can be traced back to three decades age. In year 1970s, Gulkan and Sozen [3] proposed an approach of substitute structure using the equivalent linear systems associated with equivalent stiffness and equivalent viscous damping to predict the responses of nonlinear structures. Recently, the concept was adopted (Kowalsky et al. [4]; Moehle [5]; Calvi and Kingsley [6]; Priestley et al. ([7-9]); Lin et al. [10]) for designing the single degree-of-freedom (SDOF) and multi-degree of freedom (MDOF) bridges or buildings. Besides, Wallace [11]; Sasani and Anderson [12]; Bachman and Dazio [13] focus on buildings with wall systems. In addition to the substitute structure approach, based on the relations of displacement responses between elastic and inelastic systems, Court and Kowalsky [14] presented an equal displacement-based design procedure for buildings with longer periods. Chopra and Goel [15]; Fajfar [16] modified the direct displacement-based design procedure using inelastic design spectra.

In order to get the yield displacement of the designed nonlinear structure, all of the above studies especially for Kowalsky et al. [4]; Chopra and Goel [15] always requires a repeatedly iterative procedure no matter the substitute structure or the inelastic design spectra was used in the direct displacement-based seismic design method. This will sometimes result in inefficiency if several iterative cycles need to be produced in a design case for convergency. To simplify and improve the efficiency of the procedure, a non-iterative direct displacement-based design procedure for steel bridges was presented in this paper, which used the well-known constant-ductility design spectra instead of the elastic design spectra for substitute structures (equivalent linear systems) to estimate the force and the displacement responses of the designed nonlinear systems.

II. THE INELASTIC DESIGN SPECTRUM

The force-displacement relation of a bilinear SDOF system was shown in Fig.1, where K, α, Vy , Vu , Δ_y, Δ_u and μ are the elastic stiffness, post yield stiffness ratio, yield force, maximum force, yield displacement, target (maximum) displacement and ductility ratio ($\mu = \Delta_u / \Delta_y$), respectively. If an elastic design spectrum was given, the earthquake-induced displacement of the system can directly be determined from the elastic design spectrum. The maximum displacement (Δ_u) of this systems is presented by

$$\Delta_u = \mu \Delta_y \tag{1}$$

And, the yield displacement can be obtained from pseudo-acceleration

$$\Delta_y = \omega_n^2 A_y = \frac{T_n^2}{4\pi} A_y \tag{2}$$

where A_y is the pseudo-acceleration corresponding to the yield force (Vy) and Tn is the elastic natural period of the bilinear system. Substituting Eq.(2) into Eq.(1), yields

$$\Delta_u = \mu \frac{T_n^2}{4\pi} A_y \tag{3}$$

If the ductility reduction factor (R_μ), the reduction factor due to the ductility of structures, is defined by

$$R_\mu = \frac{V_e}{V_y} = \frac{A}{A_y} \tag{4}$$

Then, Eq.(3) can be rewritten as

$$\Delta_u = \mu \frac{T_n^2}{4\pi} \frac{1}{R_\mu} A \tag{5}$$

where V_e is the elastic force for the structure to remain elastically during the design earthquake. A is the pseudo-acceleration of the elastic design spectrum.

For the ductility reduction factor, several studies have been made (Miranda and Bertero, [17];

ATC-19 [18]). In this paper, the formulae proposed by Newmark and Hall [19] will be used. They not only provide reasonable accurate results, but are also very simple and suited for the use in the direct displacement-based design method.

$$R_\mu = \begin{cases} 1 & T_n \le 0.03\,\text{sec} \\ \sqrt{2\mu - 1} & 0.125 \le T_n \le 0.66\sqrt{2\mu-1}/\mu \\ \mu & T_n \ge 0.66\,\text{sec} \end{cases} \tag{6}$$

Linear interpolations can be applied between the ranges of 0.03sec< T_n <1.125sec and $0.66\sqrt{2\mu-1}/\mu < T_n < 0.66\,\text{sec}$. Fig.2 diagrams the ductility reduction factors. It showed that the ductility reduction factor is identical to ductility ratio in the velocity –sensitive region (i.e., $T_n \ge 0.6\,\text{sec}$).

According to Eq.(5), the inelastic displacement design spectra with various ductility ratios can be obtained form the elastic acceleration design spectrum. For example, if the elastic design spectrum proposed by Newmark and Hall [19] (Fig.3) is adopted, the inelastic displacement design spectra with various ductility ratios can be shown in Fig.4. Notice that the elastic design spectrum of Fig.3 is a 5% damped, median-plus-one-standard-deviation spectrum created for a peak ground displacement of 91.4 cm (36 in), a peak ground velocity of 122 cm/sec (48 in/sec) and a peak ground acceleration of 1.0g.

III. FUNDAMENTALS OF THE NON-ITERATIVE DIRECT DISPLACEMENT-BASED DESIGN PROCEDURE

For the given SDOF steel system shown in Fig.1a, the yield force (V_y) and the yield moment (M_y) are respectively as

$$V_y = K\Delta_y = \frac{3EI}{h^3}\Delta_y \tag{7}$$

$$M_y = V_y h = SF_y \tag{8}$$

where K and Δ_y are the lateral stiffness and the yield displacement of the system, respectively. E and F_y are the elastic modulus and the yield stress of steel materials, respectively. Moreover, I and S are the moment of inertia and the section modulus of the used steel cross-section, respectively. h is the height of the column. Substituting V_y of Eq.(7) into Eq.(8) and rearranging it, yields

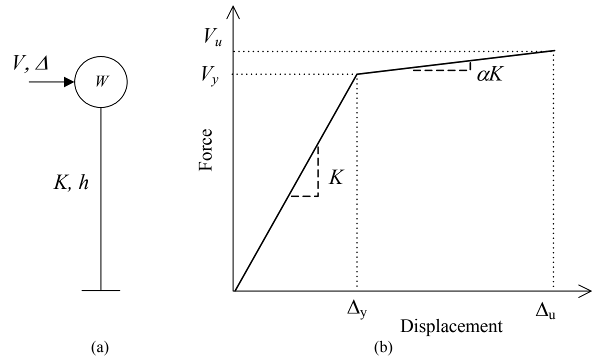


Fig.1 Force-displacement relation of bilinear SDOF systems

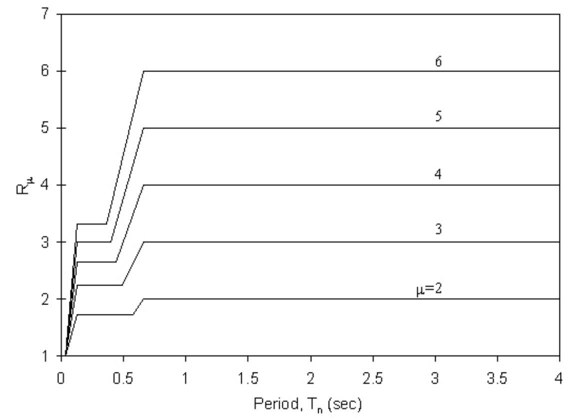


Fig.2 R_μ proposed by Newmark-Hall(1982)

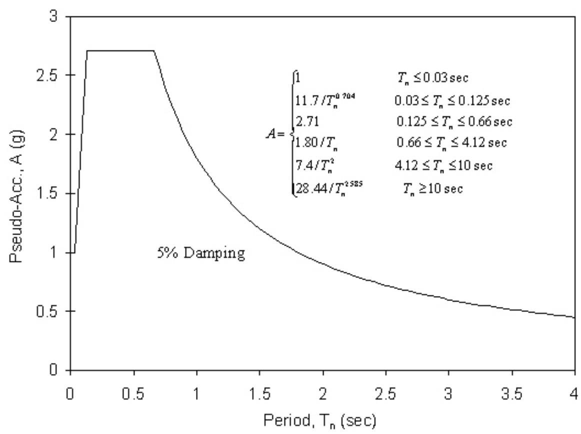


Fig. 3 Newmark-Hall elastic design spectrum(1982)

$$\left(\frac{3EI}{h^3}\Delta_y\right)\text{h=}\,SF_y \;\rightarrow\; \frac{I}{S} = \frac{F_y h^2}{3E\Delta_y} \tag{9}$$

Since existing the relationship of $S = \dfrac{I}{b/2}$ between the moment of inertia and the section modulus, thus replace $\dfrac{I}{S}$ with $\dfrac{b}{2}$ in Eq.(9) to obtain the width (b) of the designed section as

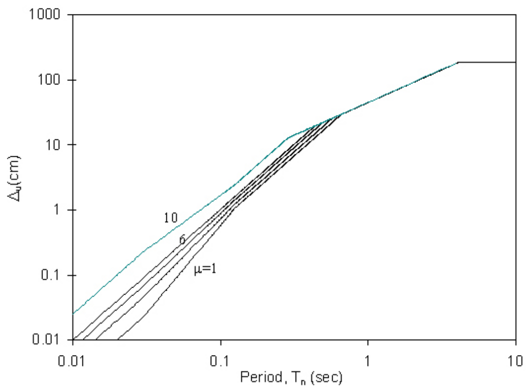


Fig.4 Inelastic displacement design spectrum (PGA=1g) derived from Newmark-Hall elastic design spectrum

$$\frac{b}{2}=\frac{F_y h^2}{3E\Delta_y} \rightarrow b=\frac{2F_y h^2}{3E\Delta_y} \qquad (10)$$

According to Eq.(10), the width of the designed section can be determined. It shows from Eq.(10) that the section width of the designed members depends only on Δ_y and h when the elastic modulus (E) and the yield stress (Fy) of steels are pre-determined. However, the yield displacement (Δ_y) of a system has a closed relationship with target displacement (Δ_u) and ductility (μ). That is $\mu=\Delta_u/\Delta_y$.

If a square box section was used (Fig.5), the moment of inertia is $I=\frac{1}{12}[b^4-(b-2t)^4]$ and the thickness (t) of the square box section can be determined from Eq.(8) as

$$M_y=SF_y \rightarrow M_y=\frac{I}{b/2}F_y$$

$$\rightarrow M_y=\frac{\frac{1}{12}[b^4-(b-2t)^4]}{b/2}F_y$$

$$\rightarrow t=\frac{1}{2}[b-\sqrt[4]{b^4-\frac{6M_y b}{F_y}}] \qquad (11)$$

In addition, if a circular hollow section is used (Fig.5), the moment of inertia is $I=\frac{\pi}{64}[D^4-(D-2t)^4]$. The thickness of the circular hollow section can also be determined from Eq.(12) as

$$M_y=SF_y \rightarrow M_y=\frac{I}{D/2}F_y \rightarrow$$

$$M_y=\frac{\frac{\pi}{64}[D^4-(D-2t)^4]}{D/2}F_y$$

$$\rightarrow t=\frac{1}{2}[D-\sqrt[4]{D^4-\frac{32M_y D}{F_y}}] \qquad (12)$$

It can be seen from Eqs.(11),(12) that the thickness of the designed members depends on the width and the yield moment of the design section for a chosen yield stress (Fy).

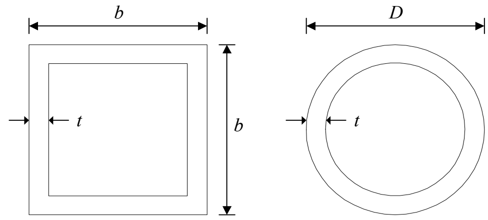


Fig.5 The square box section and circular hollow section

IV. STEP-BY-STEP PROCEDURE

A non-iterative direct displacement design procedure for steel bridges using inelastic design spectrum is shown as following steps (Fig.6):

1. Choose a target displacement (Δ_u) and a ductility ratio (μ) for the designed structure. Notice that difference to the studies of Kowalsky et al. [4]; Chopra and Goel [15], the ductility ratio (μ) of the design structure can be pre-determined in the proposed non-iterative method.
2. The yield displacement (Δ_y) then can be calculated as $\Delta_y=\Delta_u/\mu$.
3. Enter the inelastic displacement design spectrum with known Δ_u and μ to read the elastic period Tn as shown in Fig. 4. Alternatively, the elastic period can be implemented numerically as Eq.(13).

$$T_n=2\pi\sqrt{\frac{R_y}{A}\Delta_y} \qquad (13)$$

4. Calculate the elastic stiffness (K) of the non-linear system.

$$K=M(\frac{2\pi}{T_n})^2 \qquad (14)$$

where M is the mass of the system.

5. Obtain the yield force (Vy) and the design yield moment (M_y). According to Fig.1b, the design yield force (Vy) and the design yield moment (M_y) of the bilinear structure can be determined as.

$$V_y=K\Delta_y \qquad (7)$$

$$M_y=V_y h \qquad (8)$$

6. Design structural members.
   According to Eq.(10), the width (b) or diameter (D) of the designed section is

$$\text{b or D} = \frac{2F_y h^2}{3E\Delta_y} \tag{10}$$

If a square box section is used, the thickness (t) of the square box section are

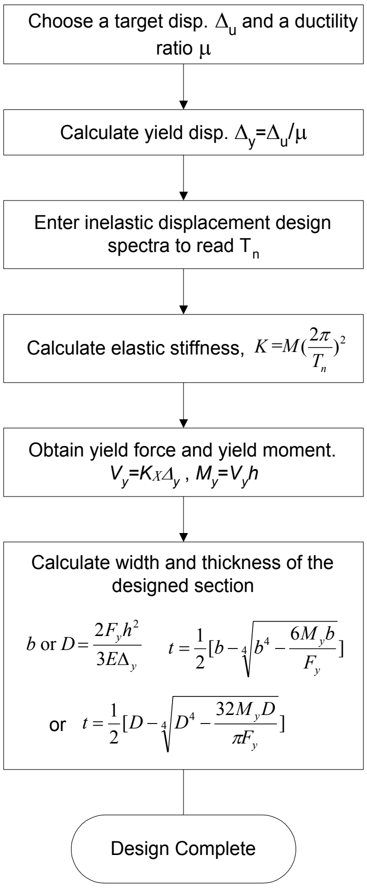


Fig.6 Flowchart of the non-iterative direct displacement-based design procedure using inelastic design spectrum

$$t = \frac{1}{2}[b - \sqrt[4]{b^4 - \frac{6M_y b}{F_y}}] \tag{11}$$

In addition, if a circular hollow section is used, the thickness (t) of the circular section are

$$t = \frac{1}{2}[D - \sqrt[4]{D^4 - \frac{32M_y D}{\pi F_y}}] \tag{12}$$

V. EXAMPLES

The presented non-iterative procedure of direct displacement-based design for steel structures using inelastic design spectra will be illustrated in following two examples. These examples are similar to the examples shown in Chopra and Goel [15]. The elastic fundamental period of the first example falls in the velocity-sensitive region of the design spectrum. However, the elastic fundamental period of the second example falls in the acceleration-sensitive region of the design spectrum.

Example 1

Referring to the paper of Chopra and Goel [15], this case is a portion of a steel bridge. The total weight of the superstructure (190 kN/m) is supported on identical bents 9m high, uniformly spaced at 39.6m. Each bent consists of a single circular hollow column. For the transverse ground motion, the viaduct can be idealized as a SDOF system (Fig.7) with the mass of M=W/g= 190 $^{KN}\!/_{m}$ ×39.6m/9.81= 767 ton. The inelastic displacement design spectra are defined by Fig. 4 scaled to a peak ground acceleration of 0.5g, which was derived from Eq.(5). The yield stress of steel material (Fy) is 250000 $^{KN}\!/_{m^2}$ and the modulus of elasticity of steel (E) is 2.0×10^8 $^{KN}\!/_{m^2}$.

1. In this example, a drift ratio of 3% and a ductility of 4 are chosen, then Δ_u=3%*9m=0.27m.
2. The yield displacement can be calculated as $\Delta_y = \Delta_u / \mu$ =0.27/4=0.0675 m.
3. Enter the inelastic displacement design spectrum with Δ_u =0.27 m and μ =4. This spectrum (Fig.8) gives Tn=1.207 sec.
4. The elastic stiffness (K) of the non-linear system is $K = M(\frac{2\pi}{T_n})^2 = 767(\frac{2\pi}{1.207})^2 = 20760$ $^{KN}\!/_{m}$
5. The yield force and yield moment are respectively as following

$$V_y = K \times \Delta_y = 20760\times0.0675 = 1402 \text{ KN} \tag{15}$$

$$M_y = V_y h = 1402 \text{ KN}\times9\text{m} = 12610 \text{ KN-m} \tag{16}$$

6. According to Eq.(10) and Eq.(12), the diameter (D) and the thickness (t) of the circular hollow column are respectively obtained as

$$\text{D} = \frac{2F_y h^2}{3E\Delta_y} = \frac{2\times250000\times9^2}{3\times2.0\times10^8\times0.0675} = 1.0 \text{ m} \tag{17}$$

$$t = \frac{1}{2}[D - \sqrt[4]{D^4 - \frac{32M_y D}{\pi F_y}}]$$

$$= \frac{1}{2}[1.0 - \sqrt[4]{1.0^4 - \frac{32 \times 12610 \times 1.0}{\pi \times 250000}}] \quad (18)$$
$= 0.083\text{m}$

It is clear from the design examples that the proposed direct displacement-based design procedure doesn't need iterations. Once the target displacement and the ductility ratio were chosen, the cross-section dimensions of the designed example can be easily determined.

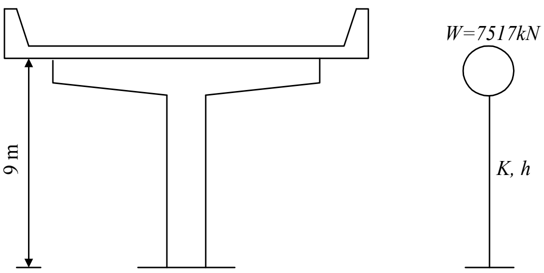


Fig.7 Bridge example and idealized SDOF system.

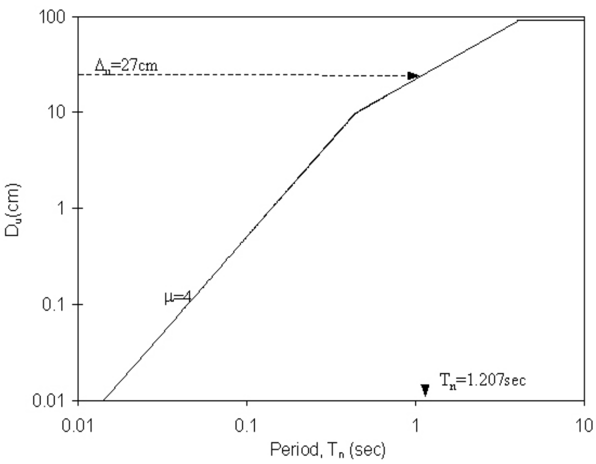


Fig. 8 Inelastic Displacement Design Spectrum (PGA=0.5g) Derived from Newmark-Hall Elastic Design Spectrum

Example 2

The second example is the same as Example 1 except that the height of the bents is 5 m. The elastic fundamental period of this system falls in the acceleration-sensitive region of the design spectrum. For this system, a drift ratio of 2.5% and a ductility of 6 are chosen. Following the proposed non-iterative procedure procedure, it is obtained that Δ_u =0.125m, Δ_y =0.021m, Tn=0.562 sec, K =95780 $^{KN}\!/_m$, V_y =1995 KN, M_y =9977 KN-m. The diameter (D) and the thickness (t) of the circular hollow column are 1.0m and 0.061m, respectively. Also, the proposed direct displacement-based design procedure doesn't need iterations.

VI. VERIFICATIONS

6.1 Using the procedure suggested by Chopra and Goel

In order to assess the performance of the proposed non-iterative procedure for direct displacement-based design, the following steps were carried out. If a system with known elastic stiffness (K), mass (M) and yield force (V_y), the target displacement (Δ_u), yield displacement (Δ_y) and ductility ratio (μ) can be computed from the procedure suggested by Chopra and Goel [15] in slightly modified form.

1. Calculate the elastic period (T_n) from the known mass (M) and the elastic stiffness (K), i.e. $T_n = 2\pi\sqrt{M / K}$.
2. Calculate the yield displacement (Δ_y) from the known elastic stiffness (K) and the yield force (V_y), i.e. $\Delta_y = V_y$/K.
3. Determine the pseudo-acceleration A form the elastic design spectrum of Fig.3. Then, the elastic design force, $V_e = (A / g)W$.
4. Once V_e is computed from Step 3, the ductility reduction factor ($R_\mu = V_e / V_y$) can be calculate, in which V_y is known yield force of the designed structure.
5. Using the $R_\mu - \mu - T_n$ relations of Eq.(6) or Fig.2, the ductility ratio (μ) can be determined. In Eq.(6), the R_μ is obtained from Step 4 and the T_n is obtained from Step 1.
6. Calculate Δ_u from $\Delta_u = \mu\Delta_y$, where the μ is obtained from Step 5 and the Δ_y is obtained from Step 2.

Following the above steps, the two example bridges designed by the proposed non-iterative procedure can be verified.

Example 1

For the final design of Example 1, K = 20760 $^{KN}\!/_m$ and V_y =1402 KN . (1). The elastic period, $T_n = 2\pi\sqrt{M / K} = 2\pi\sqrt{767 / 20760}$ =1.207sec; (2). The yield displacement, Δ_y = V_y /K = z1402/20760=0.0675m; (3). Form the elastic design spectrum of Fig.3, A=0.746g for $T_n = 1.207\,\text{sec}$ and PGA=0.5g. Then, the elastic design force, $V_e = (A/g)W$ = (0.746g/g)7524= 5613 KN ; (4). The ductility reduction factor, $R_\mu = V_e / V_y$ = 5613/1402 = 4.004; (5). Form Eq.(6) or Fig.2, $\mu = R_\mu$ =4.004 for $T_n = 1.207\,\text{sec}$; (6). The target displacement, $\Delta_u = \mu\Delta_y$ =4.004×0.0675m = 0.2703m.

In design the structure by the proposed non-iterative procedure using inelastic design spectra, the target displacement, yield displacement and ductility ratio were 0.27m, 0.0675m and 4, respectively. When the designed structure is verified using the above steps suggested by Chopra and Goel, the target displacement, yield displacement and ductility ratio are 0.2703m, 0.0675m and 4.004, respectively. It is clear that the proposed non-iterative procedure of direct displacement-based design can obtain satisfactory results for a selected performance objective.

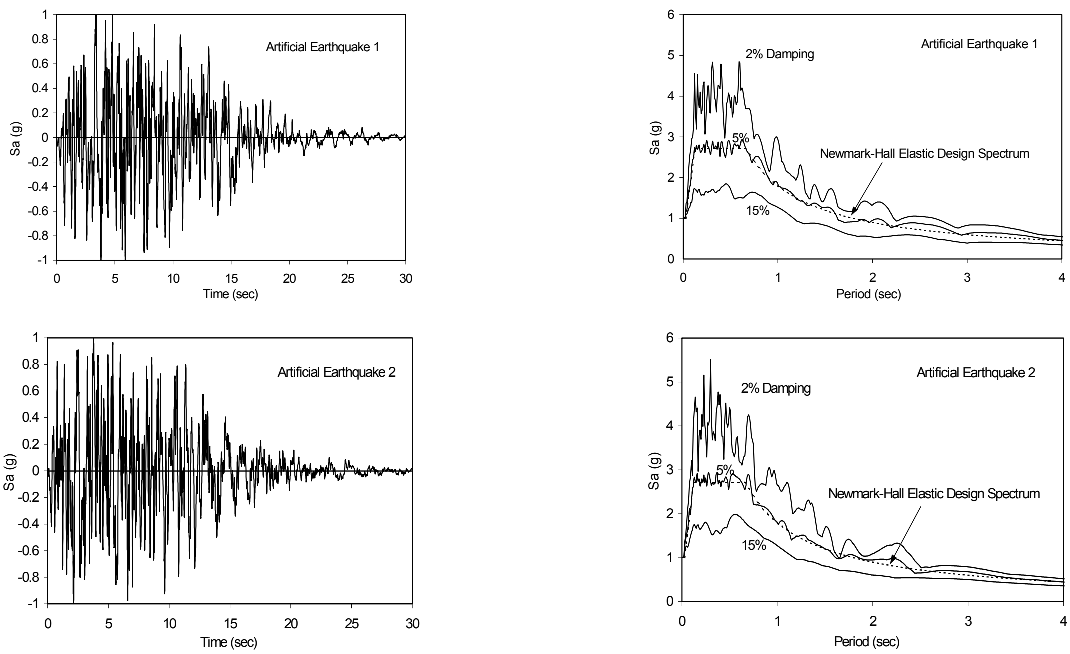
Example 2

For the final design of Example 2, K = 95780 $^{KN}\!/_{m}$ and V_y =1995 KN . (1). The elastic period, $T_n = 2\pi\sqrt{M/K} = 2\pi\sqrt{767/95780}$ =0.562sec; (2). The yield displacement, Δ_y = V_y /K = 1995/95780=0.0208m; (3). Form the elastic design spectrum of Fig.3, A=1.355g for $T_n = 0.562\,\text{sec}$ and PGA=0.5g. Then, the elastic design force, $V_e = (A/g)W$ = (1.355g/g)7524= 10195 KN ; (4). The ductility reduction factor, $R_\mu = V_e / V_y$ = 10195/1995 = 5.11; (5). Form Fig.2, μ =6.03 for $T_n = 0.562\,\text{sec}$ and R_μ =5.11; (6). The target displacement, $\Delta_u = \mu\Delta_y$ =6.03×0.0208m=0.1254m.

In design the structure by the proposed non-iterative procedure using inelastic design spectra, the target displacement, yield displacement and ductility ratio were respectively 0.125m, 0.021m and 6, which are almost the same as the values of 0.1254, 0.0208 and 6.03, respectively, determined from the steps suggested by Chopra and Goel [15].

6.2 Using dynamic nonlinear time-history analysis

The dynamic inelastic time-history analyses were carried out by the Drain-2D+ program (Tsai et al. [20]). For the two design examples, a summation of comparison of the target displacement and yield displacement under three artificial earthquakes (Fig.9) generated from the Newmark-Hall elastic design spectrum of Fig.3 were made in Table 1. The selected history responses were also shown in Figs.10. It can be seen from the table and figures that the target displacement and yield displacement of the nonlinear structures can be reliably predicted by the proposed non-iterative procedure.



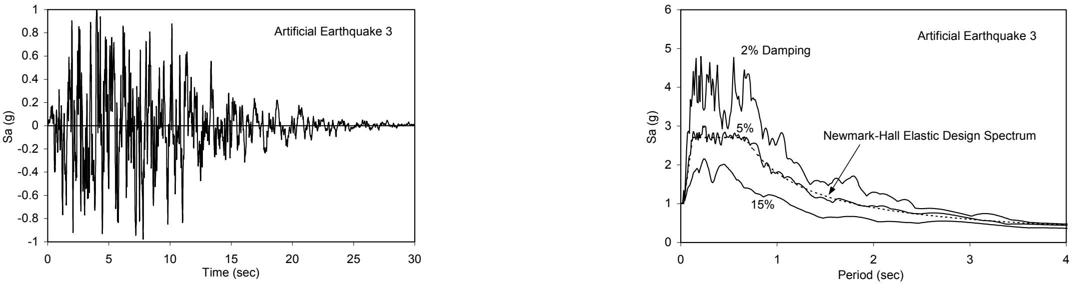


Fig.9 Artificial earthquakes generated from newmark-hall elastic design spectrum

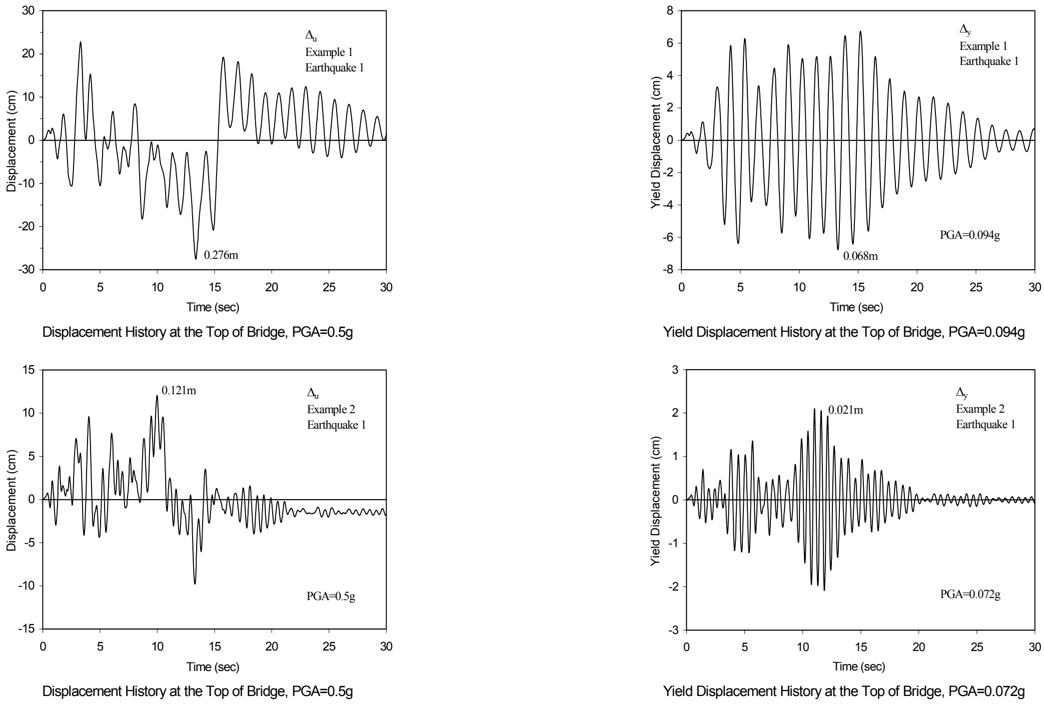


Fig.10 Selected time-history of displacement at the top of bridge

Table.1 Verifications of non-iterative direct displacement-based design using dynamic nonlinear analysis.

			Design Value	Dynamic Nonlinear Analysis	
Example 1	Δ_u (m)	Earthquake 1	0.27	0.276	0.5g
		Earthquake 2		0.282	0.5g
		Earthquake 3		0.260	0.5g
	Δ_y (m)	Earthquake 1	0.0675	0.068	0.094g
		Earthquake 2		0.068	0.089g
		Earthquake 3		0.068	0.092g
Example 2	Δ_u (m)	Earthquake 1	0.125	0.121	0.5g
		Earthquake 2		0.109	0.5g
		Earthquake 3		0.116	0.5g
	Δ_y (m)	Earthquake 1	0.021	0.021	0.072g
		Earthquake 2		0.021	0.082g
		Earthquake 3		0.021	0.066g

VII. CONCLUSION

Performance-based engineering is a trend of the structural seismic design in the 21st century. The direct displacement-based design is one of the most important methods for performance-based seismic engineering. It is a more rational and more accurate method to design structures than traditional force-based design. This procedure addresses the following problems with the force-based design: (1) eliminates the need for the use of a force reduction factor and an estimate of the structural period; and (2) provides a rational seismic design procedure that is compatible with the philosophy that structures are designed to undergo plastic deformation in a large earthquake while satisfying service criteria in small earthquakes. The only initial design parameters of the direct displacement-based design are the target displacement and the ductility ratio of the designed structures. Strength and stiffness are results of the design procedure and are dependent on the chosen target displacement and ductility ratio.

However, in order to obtain the target displacement or yield displacement of the designed nonlinear structures, the direct displacement-based seismic design method proposed by several researchers in recent years always requires a repeatedly iterative procedure no matter the equivalent linear systems (substitute structure) or inelastic design spectra was used. In order to simplify and improve the efficiency of the method, a non-iterative direct displacement-based design procedure for steel bridges has been presented in this paper, which combines the stiffness with the yielding properties of the designed cross-section to inelastic design spectrum for estimating the force and the displacement responses of the nonlinear systems. Examples were implemented to illustrate the proposed procedure. In addition to use the procedure suggested by Chopra and Goel [15], dynamic nonlinear time-history analyses for the designed examples were also carried out to asses the accuracy of the proposed non-iterative procedure. It shows from these verified analyses of the examples that the target displacement and yield displacement of the designed systems can be well predicted by the proposed non-iterative procedure of direct displacement-based design using inelastic design spectrum. Furthermore, it is interesting to note that no any linear or nonlinear analysis programs are needed when producing the proposed design method.

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