Proceedings of International Structural Engineering and Construction, 7(2), 2020
Emerging Technologies and Sustainability Principles
Edited by Askarinejad, H., Yazdani, S., and Singh, A.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2020.7(2).STR-12

DIRECT DISPLACEMENT-BASED DESIGN OF A BUILDING INCORPORATING VISCOUS DAMPERS

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The Direct Displacement-Based Design (DDBD) method has become a popular seismic design tool for structures. It takes drift as the performance criterion while designing structures. This method overcomes the shortcomings of the traditional force-based seismic design method, which considers peak force as the design parameter. In terms of structural damage, deflection is a better indicator, and hence, DDBD is a more acceptable method for seismic design. In this paper, a 12-story RC frame building with supplemental damping has been designed and investigated using a direct procedure of calculation, while considering the displacement-based design method. The performance of building with and without viscous dampers for a particular performance level has been compared. The effects of the non-linearity of dampers have also been discussed, and the effect of constant and story proportional drift proportional damper forces have been investigated. The results of various cases have been compared. It has been found that drift proportional story shear proportional carried damper design leads to construction economy.

Keywords: DDBD, Inter-story drift, Proportional distribution, Non-linearity of damper, Performance level.

1 INTRODUCTION

Traditional force-based design method has many shortcomings, such as how it considers peak force as design criteria. DDBD overcomes these shortcomings and is an efficient method for seismic designing and retrofitting of structures. It also considers drift as the target performance criterion and is performance-oriented.

Fluid viscous dampers is a very popular passive supplemental energy dissipation device. Many procedures have been developed in recent years for the direct calculation of supplemental damping required for a particular performance level. Kim *et al.* (2008) proposed a performance-based design of added viscous dampers using capacity spectrum. Moreover, many researches have been made on the displacement-based design of viscous dampers for seismic retrofit of existing buildings (Kim and Choi 2006, Lin *et al.* 2008).

Sullivan and Lago (2012) proposed a DDBD procedure for the seismic design of moment-resisting frames with viscous dampers. In this study, only linear dampers have been considered. Moreover, the proportion of story shear carried by dampers has been considered constant along the height of a building. Moradpour and Dehestani (2019) extended the previous method for non-linear dampers. Optimum distribution of dampers along the height of a structure has also been achieved in said study.

The present study is on reinforced concrete building with dampers. Both linear and non-linear dampers have been considered. The drift proportional damping has also been considered.

The scope of the present study includes (i) Building without dampers (ii) Building with linear and non-linear dampers, incorporating drift proportional damping in the dampers. Furthermore, there are two distinct studies: Case I where story shear carried by dampers is taken as constant and Case II where story shear carried by dampers is proportional to the inter-story drift. For the purpose of the study, a 12-story RC frame building has been considered. The plan is square with three bays of 5 m in each direction. The results of both cases have been compared. Also, the effect of damper non-linearity on supplemental damping to be provided has been discussed.

2 DDBD PROCEDURE TO CALCULATE SUPPLEMENTAL DAMPING

The procedure used in the present study is based mainly on Sullivan and Lago (2012) and Moradpour and Dehestani (2019), with some customizations as have been found necessary. In this study, the values taken are maximum story in building n is 12, design drift θ_d as 2%, and all story height is constant to 3 m. Floor mass of the 1st to the 4th floor is 284×10^3 kg, 5th to the 8th floor mass is 281×10^3 kg, 9th to the 11th floor mass is 278×10^3 kg, and roof mass is 139×10^3 kg. The yield strength (f_y) of rebar of frame is taken as 415 MPa. The length of beam L_b is 5 m, and the depth of beam h_b is 0.45 m. The angle of the damper with horizontal is θ_{damp} 31°. The plan and elevation of the building with dampers is shown in Figure 1. The procedural steps are briefly highlighted below.

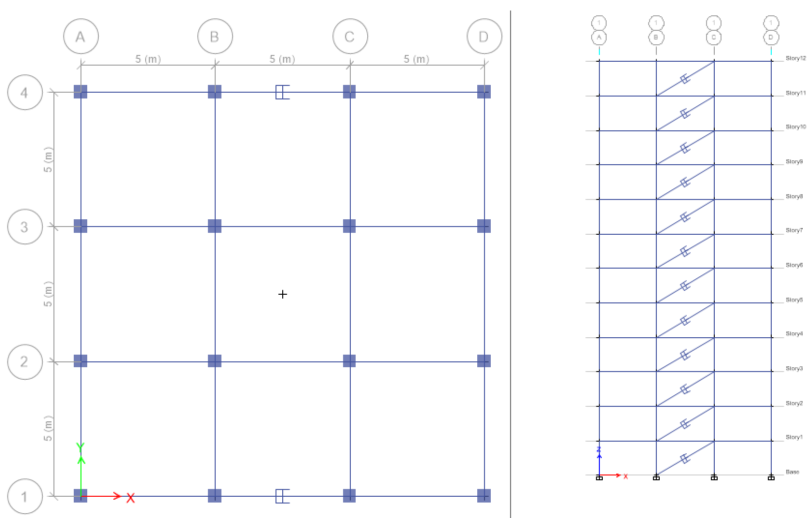

Figure 1. Plan and elevation of a typical frame of the building considered.

Step 1 Define the design displacement profile and find the equivalent single degree of freedom (ESDOF) system properties

The design displacement profile is given by Eq. (1)

$$\Delta_i = \omega_\theta \theta_c h_i \frac{4H_n - h_i}{4H_n - h_1} \tag{1}$$

where Δ_i is the lateral displacement of the i^{th} floor, ω_θ is a factor taking care of dynamic amplification whose value comes out to be unity for the present building, h_i is the height of the i^{th} floor from the base of building level, h_1 is the height of the ground story, and H is the total height of the building. The ESDOF system properties (formulae are not shown here for brevity) are as follows: design target displacement Δ_d = 0.39 m, effective mass m_e = 2640×10³ kg, effective height H_e = 23.4 m.

Step 2 Choose the proportion of design base shear to be resisted by dampers

$$F_{d,i} = {}^{\beta_i V_i}\!\big/_{\cos\theta_{damp}} \tag{2}$$

In Eq. (2), F_{di} is the design force of the i^{th} story damper, β_i is the proportion of design story shear taken by the damper, and θ_{damp} is the inclination of the damper with horizontal. As given by Moradpour and Dehestani (2019), the value of β along the height of the building can be calculated by Eq. (3).

$$\xi_{FVD} = \frac{\lambda}{2}\frac{\sum_{i=1}^{n}\beta_i V_i(\Delta_i - \Delta_{i-1})}{V_b\Delta_d} \tag{3}$$

where ξ_{FVD} is the additional damping provided by fluid viscous dampers, which has been assumed as 15%. The value for λ can be calculated from Eq. (4), in which Γ is the Gamma function, and α is the damping coefficient. It may be noted that for linear dampers, α is 1.0 and for non-linear dampers, it is less than unity. A lower value of α indicates more non-linearity.

$$\lambda = 2^{2+\alpha}\frac{\Gamma^2(1+\alpha/2)}{\pi\Gamma(2+\alpha)} \tag{4}$$

Step 3 Calculate the equivalent SDOF system damping $\xi_{eq,tot}$ as seen in Eq. (5)

$$\xi_{eq,tot} = \xi_{eq,fr} + \xi_{FVD} \tag{5}$$

where

$$\xi_{eq,fr} = 0.05 + 1.2\left(\frac{1-\mu^{-0.5}}{\pi}\right) \tag{6}$$

$$\Delta_y = 0.5H_e\frac{\varepsilon_y L_b}{h_b} \tag{7}$$

In Eq. (7), the yield strain of rebar ε_y is given by $1.1f_y/E$, where E is elastic modulus of steel and is taken as 2×10⁵. Δ_y comes out as 0.27 m, which makes the frame ductility demand $\mu = \Delta_d/\Delta_y$ = 1.44. The frame equivalent viscous damping $\xi_{eq,fr}$, which is calculated from Eq. (6), is found as 11.4%, which renders the total equivalent system damping $\xi_{eq,tot}$ as 26.4%.

Step 4 Scale the design displacement spectrum and get effective time period

The displacement spectrum corresponding to the design spectrum is scaled down for ξ_{sys}, as per Priestley (2003). From the scaled down spectrum, corresponding to the given Δ_d, the effective time period T_e is read out as 2.58 sec for building without dampers and 3.58 sec for building with dampers.

Step 5 Determine the required effective stiffness and design base shear

The effective stiffnesses calculated by using Eq. (8) for the building with and without dampers are found as 15551 kN/m and 8125 kN/m, respectively. The base shears, as per Eq. (9), for the two cases are found as 6062 kN and 3167 kN, respectively. This shows that the base shear for the building with dampers decreased by 48% of that of the building without dampers.

$$K_{eff} = 4\pi^2(m_e/T_e^2) \tag{8}$$

$$V_b = K_{eff}\Delta_d \tag{9}$$

Step 6 Calculate the equivalent lateral force and story shear at each level

The computed base shear is distributed over the floors in proportion to the floor mass and floor lateral displacement. Details are available in Pettinga and Priestley (2005). Story shears are computed.

Step 7 Calculate required design damper constant (Case I) (as per Sullivan and Lago (2012))

In this method, the value of β has been taken constant over all floors. Damper non-linearity factor α has been varied as 1.0 (linear), 0.6, 0.3, and 0.15 (highest non-linearity). The required damping constant C_i at level i for the dampers can be found by Eq. (10).

$$C_i = F_{d,i}\left(\frac{T_e}{2\pi\Delta_{d,i}}\right)^{\alpha} \tag{10}$$

where F_{di} is the design damper force at the i^{th} level, Δ_{di} is the damper displacement at the i^{th} level, which is given by Eq. (11) where θ_{di} is the story drift demand at the i^{th} level; h_s is the inter-story height; and θ_{damp} is the angle of the dampers with horizontal.

$$\Delta_{d,i} = \theta_{d,i}h_s\cos\theta_{damp} \tag{11}$$

C_i values are tabulated in Table 1. Damping constant C_i is a measure of the cost of the dampers. Table 1 shows that C_i values reduce with the non-linearity of dampers, and hence, the non-linearity of dampers makes them economical.

Table 1. Damping constants for different damper non-linearities.

STORY	**C_i (kN(s/m)$^\alpha$) (Eq. (10))**			
	α=1	**α=0.6**	**α=0.3**	**α=0.15**
12	3697	1009	377	230
11	6016	1694	648	399
10	7856	2276	890	554
9	9298	2766	1103	694
8	10420	3179	1292	820
7	11250	3514	1453	931
6	11826	3777	1588	1026
5	12178	3972	1697	1104
4	12339	4106	1780	1168
3	12317	4177	1838	1214
2	12129	4189	1868	1242
1	11789	4143	1872	1253
Total damping	121115	38802	16405	10633

Step 8 Calculate the required design damper constant (Case II) (Proposed method)

In this method, β for each story has been taken proportional to the inter-story drift ratio, which has been calculated as per Eq. (3), and is not constant. The percent inter-story drifts starting from the top are calculated as 0.77, 1.51, 2.25, 2.65, 2.60, 2.29, 1.81, 1.40, 1.14, 1.06, 1.02, and 0.58 percent. ξ_{FVD} has been kept the same as Case I, which is 15%.

The β_i values and damping constants at each level for this case have been obtained as given in Table 2 for different damper non-linearities. The percent reduction in the total damping over linear dampers and nonlinear dampers are furnished in Table 3, which has been prepared by taking damping constants from the last rows of Tables 1 and Table 2.

Table 2. β_i values and damping constants at each level for the building for different damper non-linearities.

STORY	β_i (Eq. (3))				C_i (kN(s/m)$^{\alpha}$) (Eq. (10))			
	α=1	α=0.6	α=0.3	α=0.15	α=1	α=0.6	α=0.3	α=0.15
12	0.13	0.12	0.11	0.11	1720	470	176	107
11	0.26	0.24	0.22	0.22	5506	1550	593	365
10	0.39	0.36	0.33	0.32	10710	3103	1213	755
9	0.46	0.43	0.40	0.38	14945	4447	1773	1115
8	0.45	0.42	0.39	0.37	16463	5023	2041	1295
7	0.40	0.37	0.34	0.33	15600	4872	2015	1290
6	0.32	0.29	0.27	0.26	12999	4151	1746	1127
5	0.24	0.23	0.21	0.20	10344	3374	1441	938
4	0.19	0.18	0.17	0.16	8524	2836	1230	807
3	0.18	0.17	0.16	0.15	7933	2691	1184	782
2	0.17	0.19	0.15	0.14	7491	2587	1154	767
1	0.10	0.09	0.09	0.08	4113	1445	653	437
				Total damping	116347	36548	15271	9785

Table 3. Comparison of the total damping constants in the two cases.

Case	α = 1	α = 0.6	α = 0.3	α = 0.15
β_i constant	121115	38802	16405	10633
β_i inter-story drift proportional	116347	36548	15271	9785
Percent reduction	4%	6%	7%	8%

3 NON-LINEAR TIME HISTORY ANALYSIS

The buildings designed with the above procedure have been subjected to non-linear time history analysis under five spectrum compatible ground motions. Default hinges of ETABS have been applied to the beams and columns. The maximum response out of five-time history responses gives the drift achieved. The inter-story drift diagram is shown in Figure 2 (Case I, where $\boldsymbol{\beta_i}$ is taken as constant) and Figure 3 (Case II, where $\boldsymbol{\beta_i}$ is taken proportional to the story drifts).

4 CONCLUSIONS

The DDBD method for the RC frame buildings with dampers has been highlighted in the line of Sullivan and Lago (2012) and Moradpour Dehestani (2019). Step-wise design procedure has been given. A 12-story building has been analyzed and designed (i) without dampers, (ii) with dampers having constant β_i (referred to as Case I here), and (iii) with dampers having β_i varying in proportion to story drift and story shear (referred to as Case II here).

As evident from Figure 2 and Figure 3, the maximum drift significantly reduces after applying the dampers in the structure. This is, however, normal. The sum value of the damping constant (C_i) is a measure of the cost of dampers (manufacturing cost). The total damping constant significantly decreases as the non-linearity of dampers increases. As clearly shown in

Table 2 and Table 3, the total damping constant decreases with an increase in non-linearity (decrease of α value) of the dampers. When we compare the damping constants of Table 1 and Table 2, we find that drift proportional and story shear proportional damper design leads to a lower value of damping constant, and hence, more improved construction economy. Comparing Figure 2 and Figure 3, the drift values are very near to each other under Case I and Case II, indicating economy is attained in Case II without sacrificing drift requirement.

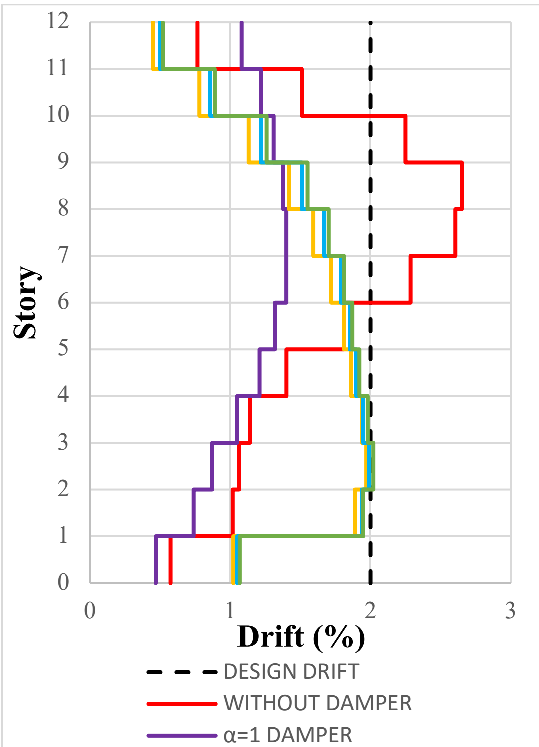

Figure 2. Drift at each level as per Case I.

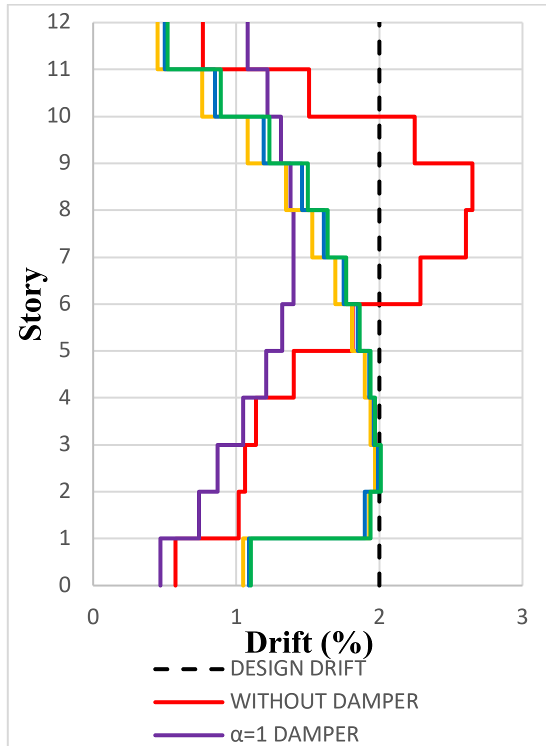

Figure 3. Drift at each level as per Case II.

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