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Displacement based design approach as a scheme stage methodology for structures with viscous dampers: some preliminary observations

A.M. Puthanpurayil
Beca, Wellington.

O. Lavan
Technion – Israel Institute of Technology, Haifa, Israel.

T.J. Sullivan
University of Canterbury, Christchurch, QuakeCore

ABSTRACT

The Direct Displacement based design (DDBD) methodology is considered to be a simple, elegant, and pragmatic approach that may be used to design viscous dampers. Some recent studies suggested that the approach may result in unconservative total estimates of damper design quantities, especially for medium and high-rise structures. In this paper, a preliminary investigation is initiated to review the effectiveness of the damper quantity derived for medium rise structures using the DDBD methodology. In that direction an existing 12-storey RC moment frame building is studied for shaking in the inelastic response range. Using the first order *gradient-based optimization* methodology, for this specific structure, it is shown that the damping quantity obtained from the DDBD framework is conservative and is ideal for scheme stage costing of a viscous damper option. It is also shown that the quantity obtained from DDBD coupled with more rigorous optimal positioning and quantification strategies results in a sustainable viscous damper design (with reduced damper quantity) achieving the performance targets.

1 INTRODUCTION

Conventional capacity design strategy relies on the "evasion" of seismic forces by enduring large inelastic deformations in the structure. This results in heavy economic losses. Past earthquakes have exemplified this aspect. The $M_w = 7.8$, 14th November 2016 Kaikoura earthquake in New Zealand is a very recent example of the economic losses mainly incurred due to the adoption of this philosophy. Although this earthquake resulted in only two deaths, the earthquake-related damages to buildings and infrastructure were roughly estimated as $\cong NZ\ \$\ 15\ billion$ (MBIE document, 2017). Similarly, the damage and business disruption in the 2010 and 2011 Canterbury earthquakes amounted to be around ≅ NZ $40 billion which corresponds to approximately 20% GDP (Pampanin 2015); it must be noted that this figure may not represent the socio-fabric disruption which would result in extensive migration of people and economic activities. Similar observations could be made from past events in other parts of the world; for example, the 1989 M6.9 Loma Prieta earthquake caused more than *US* $8 billion in direct damage (several buildings and bridges suffered total and partial collapse) although no major loss of life occurred (Wada et al., 2004). Similar observations were made for 1995 Kobe earthquake (*US* $102.5 billion in damage, 2.5% of Japan's GDP at the time) and 1999 Chi-Chi earthquake which caused about *US* $10 billion worth of damage (Wada et al., 2004).

These observations raise a major concern on the present-day seismic design philosophy as these levels of economic loss is almost unacceptable for the general public. This calls for innovative strategies which reduce damage and ensure both "life safety" and "economic safety". This expectation from the society necessitates a complete paradigm shift from the "dissipation by degradation" philosophy of the present seismic design approach to "dissipation without degradation" to achieve both "economic resilience" and "life safety". One of the ways to achieve this paradigm shift in the design philosophy is by increasing the amount of damping in the system by using either active, semi-active or passive control. In this paper the increased level of damping is achieved by adding pure viscous dampers.

Viscous dampers are mechanical devices inserted in the parent structure to increase the damping of the whole structural system. The force in a viscous damper is a function of the velocity of the damper and is related as follows:

$$\boldsymbol{f}_{damper}(t) = \boldsymbol{c_d}\ \mathcal{Sgn}\big(\dot{x}(t)\big)|\dot{x}(t)|^{\eta} \tag{1}$$

Here, $\boldsymbol{f}_{damper}(t)$ represents the damper force, $\boldsymbol{c_d}$ is the damper coefficient, $\dot{x}(t)$ is the velocity and the exponential η varies from ~0.15 to 2.0. For seismic purposes, the effective range of η is ~0.15-1.0 (Taylor 1999). This dependency of the force on the relative velocity attributes the out of phase nature to the dampers in its dynamic action thereby inducing damping and reducing the response.

1.1 Rigorous approach to damper design: state of the art

Introduction of viscous dampers into the parent structure presents itself with a highly coupled two-folded dynamic problem: the first one is to estimate the amount of damping to achieve a performance and the second one is to allocate this damping spatially in the structural system to maximise the performance. A realistic design of dampers should address this as a holistic coupled problem as the solution obtained by treating them in an un-coupled fashion might not the earn the best benefits.

Considerable research effort has been reported in the literature in this direction. One way to attack the problem is to treat it in a de-coupled manner in which the total damping is pre-assigned and rigorous optimal techniques based on classical optimisation theory are employed in allocating the dampers optimally to achieve a target performance; in other words, optimization principles are only applied in the spatial allocation and quantity estimation is based on approximated dynamic principles. Relevant works in this direction are: Zhang & Soong 1992, Tsuji & Nakamura 1996, Takewaki, 1997a, 1997b, 1998, 1999, Singh &

Moreschi, 2001, 2002, Garcia 2001. In some of these works, pragmatic approaches to estimate a reasonable total-added damping are detailed.

On a completely different perspective, alternative approaches that treat the holistic coupled problem were first presented by Lavan and Levy (2005, 2010). Both estimation of quantities of dampers and allocation was optimally done simultaneously using adaptive versions of classical first order optimization schemes. Computationally efficient gradient determination approaches are adopted in these frameworks. For more details refer to Lavan and Levy (2005, 2010), Lavan (2012, 2015a, 2015b), Puthanpurayil (2018).

1.2 Need for simplified approaches

While the above mentioned rigorous formulations lends itself to a design framework based on allowable structural responses, a considerable amount of mathematical implementation and upfront detailed analytical modelling is required to compute the quantity and spatial distribution of dampers.

From a practical engineering perspective, especially at a concept or scheme design stage, when the majority of effort from a practicing engineer is to look into the feasibility of using dampers against other low damage solutions, most of these methods described above might be non-viable options - mainly because of the frequency/time domain framework in which they are formulated. To this regard, the direct displacement-based design (DDBD) proposed by Lin et al. (2003) is a more viable option solely because of the simplified approach it adopts. This method was further improved by Sullivan and Lago (2012).

Having mentioned all the above, in a detailed-design stage the advanced rigorous approaches give very reliable and financially viable results as they target the prescribed performance. This has been highlighted in Puthanpurayil et al. (2017) for low rise structures. In Puthanpurayil et al. (2017) the preliminary results presented based on a 4-story frame shows that DDBD gives a conservative damper estimate and on application of rigorous methods described in section 1.1 the quantity of dampers could be economised.

1.3 Motivation for the present study

In a recent study by Marriott (2017), it was suggested that DDBD may result in unconservative estimates for damper quantities as the frame height increases. Designs were done, however, solely based on the distribution suggested by DDBD and to achieve the target performance, the damping quantity had to be increased which raises concerns regarding the viability of DDBD as a sole methodology even in a scheme/feasibility investigation stage for medium and high rise structures.

As some questions remain about the conclusions made by Marriot (2017), this paper presents results of a preliminary study on a medium rise RC frame in order to review possible limitations of the DDBD approach in quantifying the dampers for such systems. The results are presented as “preliminary” because further study of different structural forms in this category (medium rise) is needed to better test the method. The upper-bound nature of the method is very important as it would be easy for a designer to quantify the dampers based on this approach with some confidence in a concept design stage mainly for costing/feasibility study purposes when investigating the possibility of using dampers. Once the costing is done he/she can then apply any of the rigorous optimization framework to optimize the quantity and distribution of dampers.

2 DAMPER DESIGN APPROACHES INVESTIGATED

This section mainly outlines the design methodologies investigated in this paper.

2.1 DDBD-based approach for damper design

A full detail stepwise description of the DDBD approach is given in Sullivan and Lago (2012). The DDBD approach for damper design basically relies on the classical framework of DDBD proposed by Priestley et al (2007). The relevant steps as outlined in Sullivan and Lago (2012) are consolidated as follows:

a. Estimate an empirical design displacement profile based on a target drift.

b. Assume the proportion of the damper design base shear; normally, it is taken as follows:

$$\boldsymbol{f}_{\boldsymbol{damper,i}} = \boldsymbol{\beta V_i} \tag{2}$$

where $\boldsymbol{f}_{\boldsymbol{damper,i}}$ is the design damper force at the i^{th} level, $\boldsymbol{\beta}$ is a factor which varies from 0.3-0.6, and V_i represents the storey shear at level i. In the present study, $\boldsymbol{\beta}$ is given uniformly over the height of the building.

c. Compute the effective SDOF system viscous damping. If non-linear response of the structural system is expected, the equivalent damping this contributes can be estimated as suggested in Sullivan and Lago (2012) and combined with the damping expected from the dampers.

d. Scale the 5% target displacement spectrum to account for the damping.

e. Compute the effective period of the SDOF.

f. Compute the effective stiffness and base shear.

g. Compute member forces and damper design forces as outlined in step b.

h. Compute damper coefficients.

2.2 Optimization problem formulation

Optimisation problem described in this section is very similar to Lavan and Levy (2005), Puthanpurayil et al. (2017). The performance index is selected as the maximum of the inter-storey drifts below a selected target drift.

2.2.1 Equations of motion

The equations of motion of the nonlinear frame with added dampers are given as:

$$\mathbf{M}\ddot{\boldsymbol{u}}(\boldsymbol{t}) + \left[\mathbf{C} + \mathbf{C}_{\boldsymbol{damper}}(\mathbf{c}_{\boldsymbol{d}})\right]\dot{\boldsymbol{u}}(\boldsymbol{t}) + \mathbf{f}_s\left(\boldsymbol{u}(\boldsymbol{t}), \dot{\boldsymbol{u}}(\boldsymbol{t})\right) = -\mathbf{Mi}\ddot{u}_{\boldsymbol{g}}(\boldsymbol{t})$$

$$\boldsymbol{u}(\mathbf{0}) = \mathbf{0}; \dot{\boldsymbol{u}}(\mathbf{0}) = \mathbf{0} \tag{3}$$

In Eq. (3), $\mathbf{M}$ represents the mass matrix and $\mathbf{f}_s\left(\boldsymbol{u}(t), \dot{\boldsymbol{u}}(t)\right)$ represents the restoring forces' vector at time t. Similarly, $\mathbf{C}$ represents the inherent damping matrix. $\mathbf{C}_{\boldsymbol{damper}}(\mathbf{c}_{\boldsymbol{d}})$ is the added supplemental damping matrix and $\mathbf{c}_{\boldsymbol{d}}$ is the added damping vector. $\mathbf{i}$ represents the ground motion directional vector, and $\ddot{\boldsymbol{u}}(t), \dot{\boldsymbol{u}}(t)$and $\boldsymbol{u}(t)$ are the relative accelerations, relative velocities and relative displacements, respectively. $\ddot{u}_{\boldsymbol{g}}(\boldsymbol{t})$ is the ground acceleration.

2.2.2 Optimisation problem formulation

The optimisation problem is formulated as,

$$\min J\,(\mathbf{c}_{\boldsymbol{d}}) = \mathbf{c}_{\boldsymbol{d}}^{\boldsymbol{T}}\mathbf{1} \tag{4}$$

Eq. (4) represents minimizing the initial investment which is taken proportional to the damping material in this paper.

Subject to:

$$\mathbf{P}_i = \frac{\mathbf{\Phi}}{\mathbf{\Phi}_{allowable}} \leq \mathbf{1.0} \tag{5}$$

Here, $\mathbf{\Phi}$ refers to the maximum drift computed - based on the maximum peak response. Mathematically, $\mathbf{\Phi}$ is given as:

$$\left.\begin{array}{c} \mathbf{\Phi} = max_i\left(max_t\left(abs\left(\mathbf{d}_i(\boldsymbol{t})\right)\right)\right) \\ \text{where } \mathbf{d_i(t)} \text{ is the response vector computed using transformation matrix } \mathbf{H} \text{ as,} \\ \mathbf{d}_i(t) = \mathbf{H}_i\boldsymbol{u}(t), \\ \text{where } i' \text{ refers to the storey level and satisfies the following equation,} \\ \mathbf{M}\ddot{\boldsymbol{u}}(\boldsymbol{t}) + \left[\mathbf{C} + \mathbf{C}_{\boldsymbol{damper}}(\mathbf{c}_{\boldsymbol{d}})\right]\dot{\boldsymbol{u}}(\boldsymbol{t}) + \mathbf{f}_s\left(\boldsymbol{u}(\boldsymbol{t}), \dot{\boldsymbol{u}}(\boldsymbol{t})\right) = -\mathbf{Mi}\ddot{u}_{\boldsymbol{g}}(\boldsymbol{t}) \\ \boldsymbol{u}(\mathbf{0}) = \mathbf{0}; \dot{\boldsymbol{u}}(\mathbf{0}) = \mathbf{0} \\ \mathbf{0} \leq \mathbf{c}_{\boldsymbol{d}} \end{array}\right\} \forall\, \ddot{u}_g(t) \epsilon \textit{ whole ensemble} \tag{6}$$

2.2.3 Classical optimisation scheme

A gradient-based optimisation scheme is used for solving the nonlinear optimisation problem defined in eq. (6) (Lavan and Levy 2005, Puthanpurayil et al, 2015, Puthanpurayil 2018). Only a brief description of the gradient-based formal optimisation scheme is presented in this Section 2.2.3.1.

2.2.3.1 Gradient-based optimisation scheme

The damper-optimisation problem, as formulated in Section 2.2.2, is highly nonlinear in nature. Conceptually, the gradient-based scheme solves the nonlinear optimization problem in an incremental fashion in which the nonlinear problem domain is discretised into a set of piecewise-linear optimisation problems which are solved iteratively. Only a very brief review of the steps is given in this Section. For more details interested readers should refer to Puthanpurayil et al (2015) and Lavan and Levy (2005).

- *Selection of active ground motions*

As the main aim of the present study is to investigate the viability of the DDBD approach to be adopted in the scheming stage, a set of region compatible ground motions are scaled to a specific displacement spectrum level based on soil category. Optimization may be performed by using the full set of N ground motions; for more details refer Puthanpurayil (2018). However, in this study as the sole purpose is to investigate the performance of the DDBD method, an alternative computationally efficient approach called *active ground motion* methodology as described in Lavan and Levy (2005) is adopted in the present study. An active ground motion set may be considered as a subset of the selected suite of ground motions and is comprised of those ground motions which maximise the responses of the structure. Once the optimization for the active set of ground motions is done, the performance with respect to others is checked and additional ground motions are added to the active set as needed.

- *Computation of envelope drift responses for the inelastic frame*

Adopting an initial amount of damping vector $\mathbf{c}_d$, solve eq. (3) using any of the time integration schemes available in literature for the set of ground motions identified as *active ground motions.* In this study, the total equilibrium Newmark constant average acceleration method described in Carr (2007) and Puthanpurayil et al (2014) is used and the nonlinear force is represented using smooth mathematical non-degrading *Ozdemir hysteresis*. Although the framework itself does not require an informed selection of the initial $\mathbf{c}_d$

vector, a judicious selection will reduce the computational time involved. In this study as the viability of DDBD is being investigated, the damper vector obtained from DDBD is used as the initial vector.

- *Evaluation of performance index* $\mathbf{P}_i$

Evaluate $\mathbf{P}_i$ using eqs. (5) and (6).

- *Gradient computation of the performance index* $\mathbf{P}_i$ *and the objective function J*

Gradient for the objective function J is trivial and the sensitivity will return a vector **1.** But the gradient of the performance index $\mathbf{P}_i$ is not trivial. There are different ways in which the gradients can be computed; in this study the gradients are derived using Adjoint Variable method (AVM) using differentiate and discretize approach. This is a highly efficient method; Refer Jensen et al. (2013).

- *Estimate a new* $\mathbf{c}_d$ *for the optimal design using Sequential Linear Programming (SLP)*

The original optimisation problem given in eqs. (4-6) is discretised into piecewise-linear domains and solved using SLP. Linearisation of the objective function given by Eq. (4) at the i^{th} iteration gives:

$$J^i(\mathbf{c}_d) = J(\mathbf{c}_d^i) + \{\nabla_{\mathbf{c}_d} J(\mathbf{c}_d^i)\}(\Delta \mathbf{c}_d^i) \tag{7}$$

Linearisation of the constraint at the i^{th} iteration satisfying Eq. (5) results in,

$$\mathbf{P}_{\boldsymbol{i}}(\mathbf{c}_d) = \mathbf{P}_{\boldsymbol{i}}(\mathbf{c}_d^i) + \{\nabla_{\mathbf{c}_d} \mathbf{P}_{\boldsymbol{i}}(\mathbf{c}_d^i)\}(\Delta \mathbf{c}_d^i) \tag{8}$$

Equations (7) and (8) are solved and the incremental $\Delta\mathbf{c}_d$ vector required for the next iteration is obtained by solving a modified linear programming problem. Once $\Delta\mathbf{c}_d$ is obtained, the damping vector $\mathbf{c}_d$ is updated as:

$$\mathbf{c}_d + \Delta \mathbf{c}_{\boldsymbol{d}} \tag{9}$$

- *Check for termination condition*

The iteration is terminated if the change in the added damper vector $\Delta\mathbf{c}_{\boldsymbol{d}}$ is less than the tolerance or the maximum number of iterations has been reached. Otherwise, update the iteration number as *i=i+1* and proceed back to Step 1.0. Once an optimum quantity and distribution of dampers is obtained, check for all other ground motions in the ensemble to see whether the present optimal damper distribution violates the constraint on the drift. If it violates, then the ground motion gets added into the active set of ground motions and the optimisation steps are repeated.

3 NUMERICAL STUDY

The purpose of the present paper is to investigate the inherent conservatism in the DDBD approach so that it may be used to estimate the initial damper quantity in a scheme design stage for costing and feasibility purposes. As mentioned earlier, a similar study was presented for low rise buildings in Puthanpurayil et al. (2017). Preliminary studies indicate that for low rise systems with single mode participation, DDBD performs satisfactorily. Similar observations were made by Marriott (2017).

In this study preliminary investigations on medium rise structure is presented. In this direction, a retrofitting scenario is chosen and an older twelve-storey reinforced concrete framed building designed in accordance with NZS 4203-1992 as described in Ruiz (2005) is used for the present study. The simplified floor plan is shown in Figure 1.

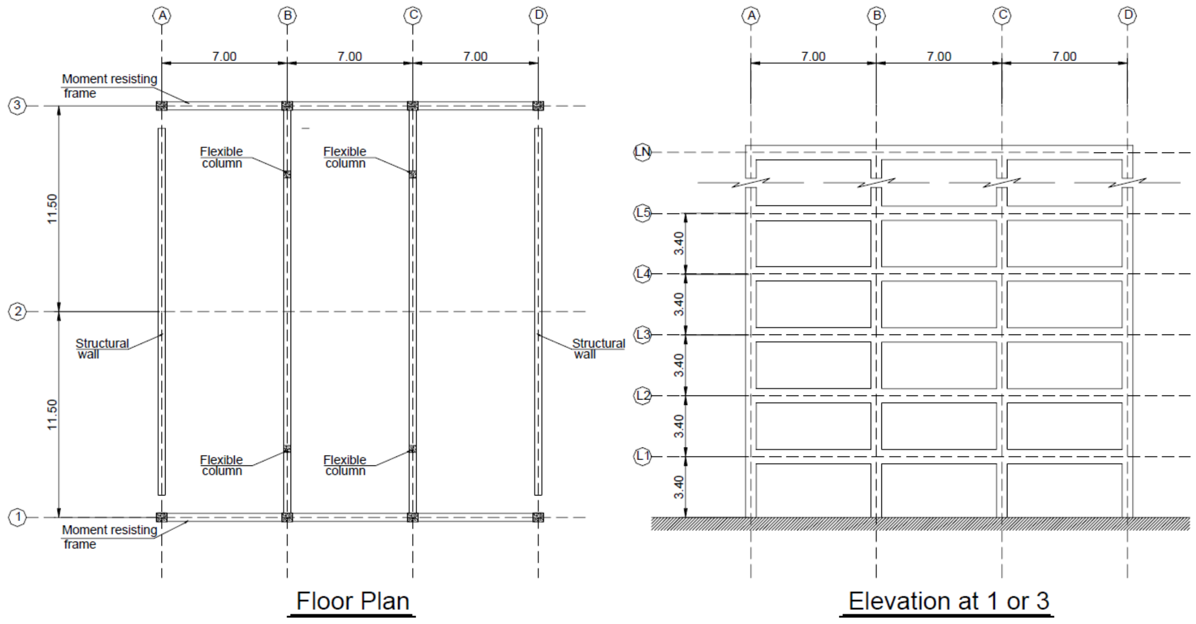

Figure 1: Floor plan and typical elevation (adopted from Ruiz, 2005).

The frame is assumed to be in Wellington and on intermediate soil classification. Material and section properties, along with the nonlinear parameters, are given in Ruiz (2005). The damper bay frame and its idealized arrangement is presented in Figure 3. A Giberson one component model is used to model the frame elements. The hysteresis is represented by a smooth non-degrading *Ozdemir hysteresis.* It's true that the idealized Ozdemir non-pinged hysteresis is not a complete realistic representation of RC mechanism in the inelastic range. But as viscous dampers are added into the structure and the drift is limited by employing a drift constraint, the whole system incurs much less plasticity as compared to an uncontrolled RC structural system. Also, as the sole purpose is to evaluate the upper boundedness of DDBD, this hysteresis is deemed to be sufficient. Inherent damping is represented by updated elemental Wilson Penzien model (Puthanpurayil 2018) as opposed to the classical Rayleigh damping model.

A target drift of 1.5 % was identified as the performance limit and DDBD design was performed using this target drift. The obtained final damper quantity from the DDBD is used as the initial damper vector for the optimization scheme presented in section 2.2.3. A β factor of 0.3 is used in the DDBD calculations.

The optimized damper distribution is obtained from the classical optimization scheme by running the active *ground motion set.* The *active ground motion set* is derived from 10 ground motions scaled to 5% damped elastic acceleration spectra for intermediate soil. The scaled spectra of actual ground motions and the target spectra is shown in Figure 2.

The algorithm described in Section 2.2.3.1 is used for formal optimization and the obtained results (damper quantities and distribution) are checked in parallel using an alternative optimization scheme. Though not shown here for clarity only a difference of around 4% is obtained by using the alternative approach.

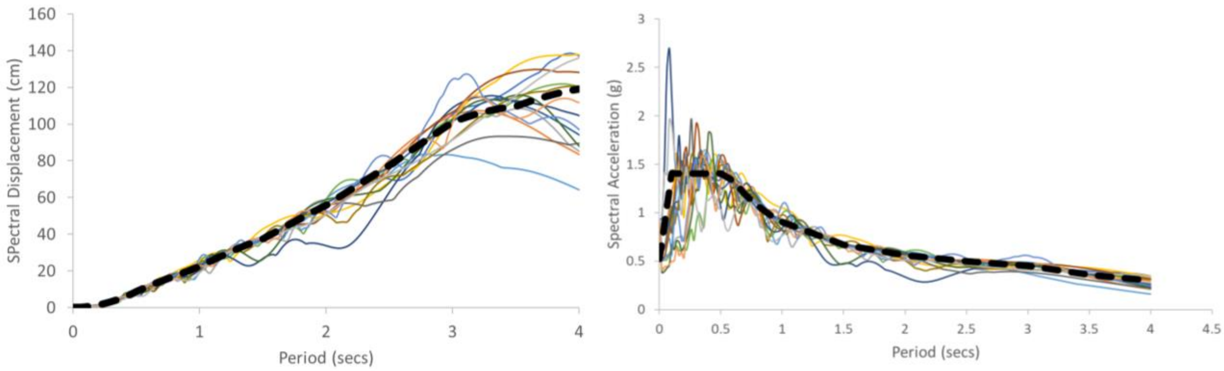

Figure 2: Displacement and acceleration spectra of scaled ground motions along with target spectra

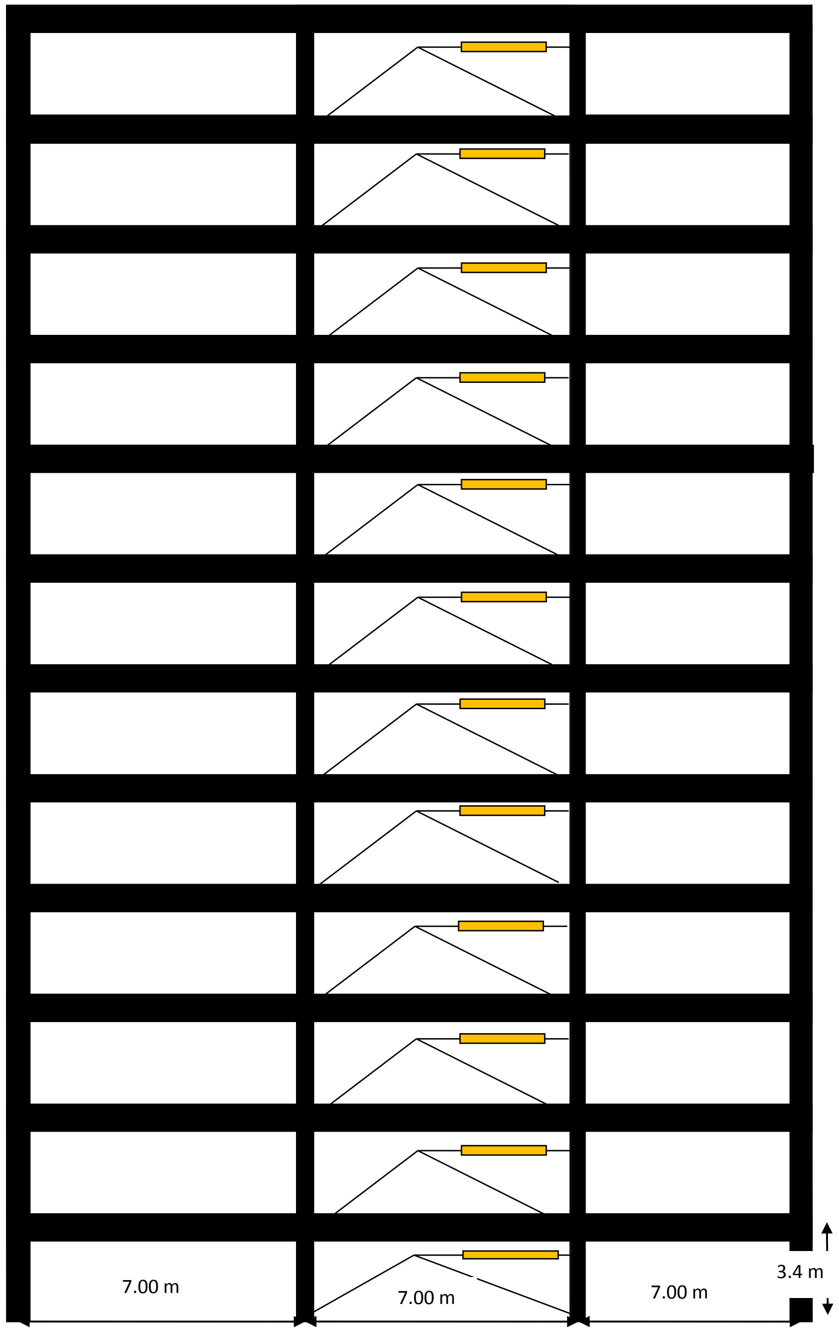

Figure 3: Damped frame elevation.

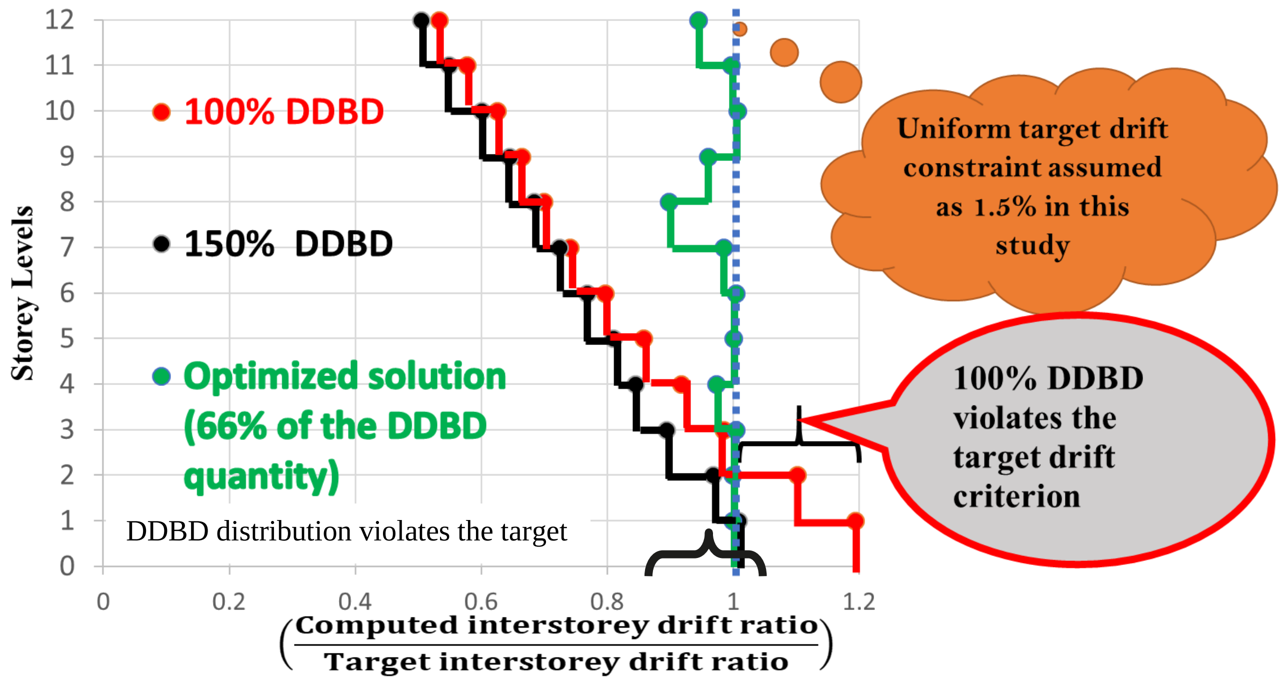

Figure 4: Normalized drift obtained by DDBD vs. Optimized solution.

Figure 4 represents the normalized drift response of the structure with the DDBD designed damping, the DDBD designed damping multiplied by 1.5 as recommended by Marriott (2017) and the optimized solution obtained by employing the framework described in section 2.0. The response shown in Figure 4 is for the ground motion in the *active set.* It can be clearly seen that if we directly adopt the distribution given by DDBD then the interstorey drift obtained exceeds the drift target by 20%in the first storey and ~10% in the second storey. Interestingly, if the distribution obtained using DDBD is multiplied by 1.5 (as suggested by Marriott, 2017), the target drift is indeed achieved, *though no conspicuous performance improvement is achieved in the upper storeys due to this 50% increase in added damping material*. Alternatively, such performance, where the target drift is achieved, may also be obtained without increasing the total amount of added damping as suggested by Marriott (2017). This can be done by optimally quantifying and distributing the dampers. This signifies the fact that initial damper estimate given by DDBD is reasonable for a scheme stage for this frame and what is needed is a more rigorous smart allocation of the quantity of dampers obtained from DDBD.

For obtaining the optimized response, the initial $\mathbf{c}_d$ vector is assumed as the DDBD distribution. The results show the significance of optimal distribution in achieving the target performance. Figure 5 gives the optimal distribution and quantities of dampers in terms of damper coefficients. Though not presented here, performance of this distribution is checked for all the other ground motions in the suite as well and it satisfies the performance criterion. Here it is assumed that the cost of the damper is directly related to the damper material quantity characterised by the damper coefficients. The distribution obtained from the optimization is very different to that given by DDBD. This is mainly because the optimization is done in real time and the instantaneous dynamic changes of the parent structure is incorporated into the design of the dampers. ***The more interesting aspect is that the target performance is achieved by the optimizer using only 66% of the DDBD damper quantity***. The total damper quantity required by DDBD is $44{,}154\ {}^{kN-sec}/_{m}$ whereas that required by the optimizer is $29{,}254\ {}^{kN-sec}/_{m}$ which is 66% of the DDBD quantity. The first mode damping ratio for DDBD quantity is ~33% and that for the optimized quantity is ~21%.

Though more substantial evidence is needed, this conservative estimate given by DDBD in this specific case (33% more than required) makes it a very good candidate for the scheme design stage as a reasonable amount of conservatism is needed at that stage. This also reinforces the hypothesis that at the detailed design stage, a more rigorous approach to the damper design using a classical optimization scheme should be employed to arrive at a more cost-effective solution. It must be acknowledged that the system studied in this paper has a high mass participation of 83% in the first mode. So, to establish the upper boundedness of the DDBD approach as a scheme stage strategy, more work needs to be done with varying systems with larger higher mode effects.

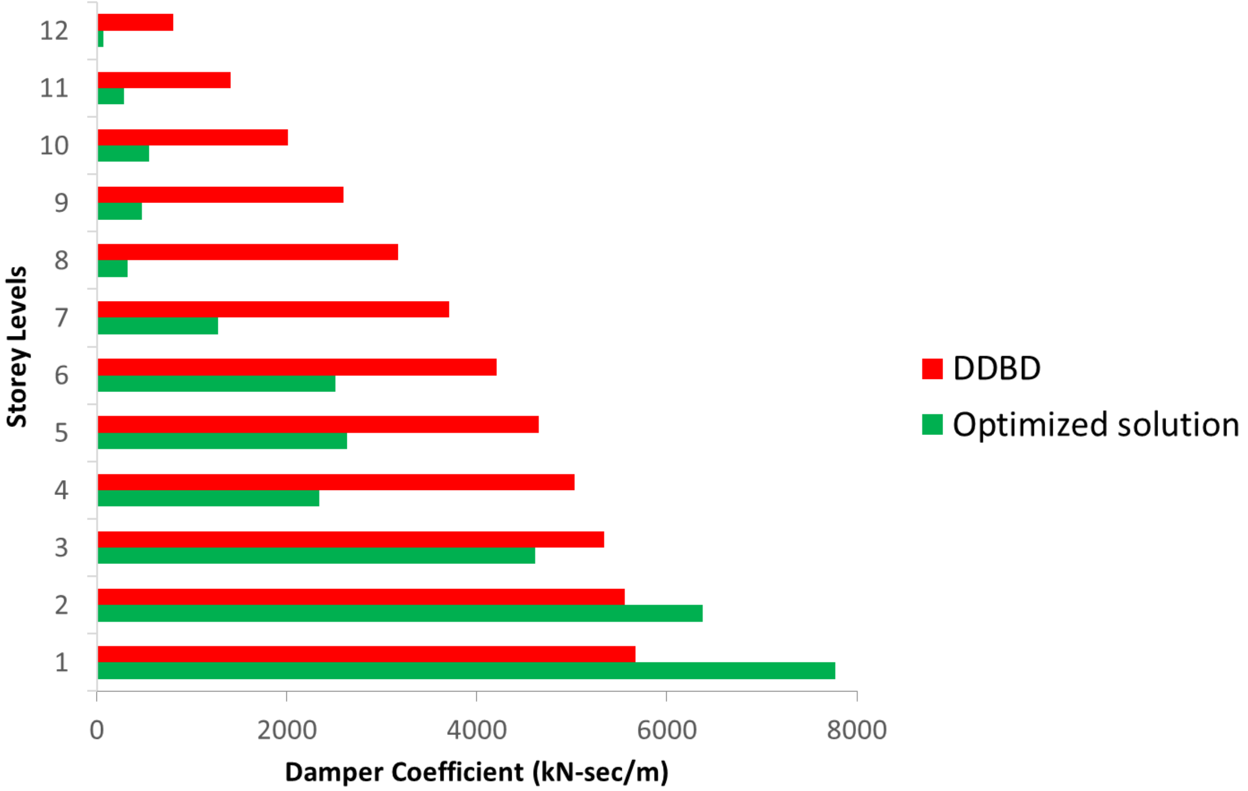

Figure: 5 Damper coefficient distribution for both DDBD and the optimized solution.

4 CONCLUSION

A preliminary investigation into the viability of using DDBD for the design of dampers in the schematic design stage for medium rise buildings is presented. The results obtained for this specific case study structure show that DDBD may give conservative results for the initial damper quantity. This may be used for costing purposes in the schematic design stage. The damping distribution, on the other hand, may lead to violation of the performance target. Thus, in the final design stage a smart damper placement methodology may be necessary; Whether DDBD based damper sizing would always give an upper bound quantity of dampers for medium-rise buildings should be further investigated. It has also been shown that for the specific case-study frame, a considerable economic advantage in terms of reduced total quantity of damping required (which is assumed to be directly proportional to the initial investment cost) for satisfying the same performance may be achieved if formal, classical optimization schemes are used in the detailed design stage. Further evidence in the form of studies on different systems is needed to establish the previous statement to its entirety.

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