Towards a direct displacement-based design procedure for cold-formed steel frame / wood panel shear walls

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SUMMARY:
Current seismic design procedures for cold -formed steel frame/wood panel (CFSFWP) shear walls utilise force-based approaches, which are recognised as having a number of shortcomings. To assist in the realization of an alternative Direct Displacement-Based seismic Design (DDBD) methodology for CFSFWP shear walls, recommendations for the equivalent viscous damping, EVD, and the design displacement profile of CFSFWP shear wall systems are provided in this paper. The EVD expression is proposed using the results of an established calibration procedure in which numerous non-linear time history (NLTH) analyses are undertaken for different SDOF systems. The results of NLTH analyses of a 3-storey case study building indicate that the design procedure is very promising and therefore future research will look to further develop and test the approach.

Keywords: Cold-formed steel, Wood-panel, Direct Displacement-Based Design, Shear wall, Equivalent viscous damping

1. INTRODUCTION

Over the past decades, cold-formed steel frame / wood-panel (CFSFWP) systems (see Fig. 1.1) have seen increased usage as the structural framing elements for low-rise buildings due to their competitiveness in relation to conventional construction systems and the increased design and construction flexibility they offer. The walls in such systems are composed of cold-formed steel profiles (studs and tracks) and wood based panels, such as Oriented Strand Board, OSB, or Plywood, which are usually connected to the steel frame by screws. These walls have the primary functions of carrying the lateral loads and in many cases they also should carry the vertical loads as well.

Current seismic design procedures for CFSFWP shear walls rely on force-based methods. Force-based design approaches are recognised (Priestley et al. 2007) as having a number of shortcomings, incorporating reduction/behaviour factors that do not account for structural proportions and likely ductility demands, being unable to correctly predict inelastic force distributions when structural systems possess elements with different yield displacements, and being sensitive to initial period estimates, amongst other things. For what regards seismic design, the importance of deformation, rather than strength, in assessing seismic performance is apparent. As argued by Priestley et al. (2007) if the design objective is to control the damage under a given level of seismic attack, it would be more reasonable to design the structures to meet a desired displacement under the design seismic intensity, and this has motivated the development of the Direct Displacement-Based Design approach (DDBD).

To develop the DDBD procedure for cold-formed steel-frame / wood-panel shear wall structures, three important parameters are needed: (i) a means of determining the displacement corresponding to important limit states for different wall configurations; (ii) expressions for the equivalent viscous damping, EVD, of CFSFWP shear walls and (iii) expressions for the design displacement profile and general design procedure for CFSFWP shear wall systems. In the authors' previous works (Moayed

Alaee ,2011), progress has been made towards satisfaction of the first of these tasks by proposing a method to estimate important drift limits and the yield displacement, Δ_y, of the walls using fastener connection test load-displacement data.

This paper provides recommendations for the equivalent viscous damping and the design displacement profile of CFSFWP shear wall systems. A new EVD expression for CFSFWP shear walls is proposed using the results of an established calibration procedure in which numerous non-linear time history (NLTH) analyses are undertaken for SDOF systems with different effective periods and for different levels of design displacements and then, as CFSFWP wall buildings are not expected to exceed 4-storeys in height, a linear design displacement profile is assumed as part of the trial DDBD procedure that has been recently developed in Moayed Alaee (2011).

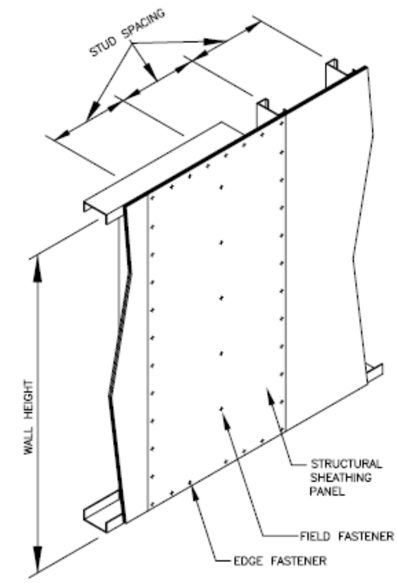


Figure 1.1. Cold-formed steel-frame/wood-panel shear wall (NASFA, 2000)

2. THE EVD OF THE CFSFWP SHEAR WALLS

The introduction of the equivalent viscous damping concept in design allows the implementation of an equivalent linear system at peak response in lieu of the original non-linear system, and this can be very useful for design and analysis. Based on this concept, in the DDBD method the equivalent linear system is characterized with a stiffness equal to the secant stiffness at maximum response and a ductility-dependent value of the equivalent viscous damping.

The equivalent viscous damping, ξ_{eq} is generally considered as the sum of elastic, ξ_{eq} , and hysteretic damping ξ_{hyst} components:

$$\xi_{eq} = \xi_{el} + \xi_{hyst} \tag{2.1}$$

ξ_{hyst} , depends on the hysteretic behaviour of the structure and was traditionally determined by equating the energy absorbed by a hysteretic steady-state cycle response to the energy absorbed by a damped steady-state cycle response for a given displacement. However, the EVD expression to be used within DDBD differs from Eqn. 2.1. since for the hysteretic component a harmonic steady state response is assumed, which cannot be expected in the case of seismic response. Moreover, for hysteretic rules in which there are no stabilized loops due to stiffness and strength degradation the definition of a stabilized loop is not easy. Therefore, alternative EVD expressions have been developed empirically from numerical analysis by different researchers (Grant et al., 2005, Dwairi et al., 2007 and Pennucci et. al, 2011) for use in the DDBD method. These EVD expressions have been developed for systems with different effective periods, T_e, and for different ductility levels, μ. The common procedure of obtaining the EVD for a set of points of (μ, T_e) for a given hysteretic rule with post-yield stiffness ratio, r, is as follows: Non-linear time history analyses of a SDOF system responding inelastically are undertaken. The system is characterized by a maximum displacement, Δ_{Max}, maximum ductility, μ, and initial period. The effective period, T_e, is then determined from characteristics of the hysteretic rule (r and T) and ductility, μ. Linear time history analyses of a system with a period equal to T_e and an increasing damping ratio are then performed and the maximum "overdamped" displacement, Δ_ξ , is compared to Δ_{Max}. The calibrated value of EVD is the damping that results in $\Delta_\xi = \Delta_{Max.}$

2.1. Energy Dissipation in CFSFWP Shear Walls

Experimental tests conducted by different researchers including the test performed at McGill University (Branston ,2004, Chen ,2004, and Boudreault, 2005) show that the energy dissipation in CFSFWP walls is approximately proportional to the number of perimeter screws, provided that the sheathing- to- framing connection failure (bearing – tilting – pullout) dominates the failure mode. In other words, the energy per screw remains almost constant for a wall with different fastener schedules and the total wall energy dissipation can be taken as the summation of the energy-dissipating capability of the individual screw fasteners. Consequently, the fastener connection tests are able to provide a general indication of the energy-dissipating characteristics of the shear walls. In the next subsections the dominant parameters that influence the EVD for different wall characteristics and in particular sheathing-to-framing fastener connection characteristics are investigated.

2.1.1. Effect of steel grade, steel thickness, sheathing thickness and edge distance

The effect of different characteristics of a sheathing-to-frame fastener connection has been investigated by Okasha (2004). Considering the test results summarized in Table 2.1, it can be concluded that the effect of steel stud strength, steel stud thickness and wood sheathing thickness on normalized energy dissipation is not significant. Likewise, the effect of edge distance can be ignored provided that minimum edge distance is respected. In this table, E is the dissipated energy during the test (in Joules) and F_y is the yield force of the wall obtained by implementing the EEEP method as proposed by Chen (2004).

2.1.2. Effect of steel wall length and fastener schedule

The experimental test results have indicated that increasing the number of screws (decreasing the fastener spacing) proportionally increases the lateral resistance of the wall. However, the displacement corresponding to the specified limit states does not follow the same trend and remains almost independent of the number of screws (see Moayed Alaee et al. ,2012). Therefore, by increasing the number of screws (denser fastener schedule), the energy dissipation and the wall resistance improve with almost the same rate and, as such, the normalized energy dissipation should remain almost constant as can be seen in Table 2.1 by comparing the normalized energy of tests that have the same sheathing type but different fastener spacing. The same logic applies for the whole length of the walls since the walls are mainly composed of identical panels with the same energy dissipation characteristics. Having no significant difference in normalized energy dissipation raises the idea that the equivalent viscous damping ratio of these systems should not be different if the sheathing panel dimensions are the same. These conditions are usually met since the majority of the sheathing panels have the same width and height in a floor.

From the above observations it is concluded that if the walls are designed for a certain level of force and the displacement demands are of the same range (i.e. torsion is not significant), the normalized energy dissipated in all the walls would be approximately equal, regardless of the fastener spacing or wall length or number of the walls. In this way, different CFSFWP shear wall configurations can be represented by determining a general EVD expression that is a function of the ductility demand.

Table2.1. Normalized energy dissipation in full scale tests

Test No. *	Sheathing	Fastener spacing (mm)	Wall length (m)	Δ_u (mm)	Normalized Energy E/F_y (mm)	$E/F_y/\Delta_u$
4	CSP	100	1.2	57	65.2	1.14
8	CSP	150	1.2	51	60.6	1.19
10	CSP	75	1.2	54	57.2	1.06
12	DFP	150	1.2	52	58.9	1.13
14	DFP	75	1.2	53	53.9	1.02
22	OSB	150	1.2	42	52.1	1.24
24	OSB	100	1.2	37	40.2	1.09
26	OSB	75	1.2	38	43.7	1.15
30	CSP	150	2.4	52	59.4	1.14
32	CSP	100	2.4	54	61.0	1.13
34	CSP	75	2.4	60	61.3	1.02

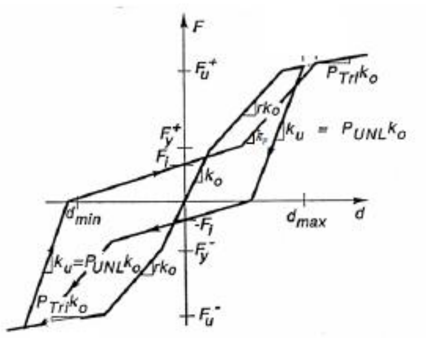
* McGill University tests conducted by Boudreault, Branston and Chen

2.1.3. Effect of sheathing type

CFSFWP walls with OSB panels have a similar hysteretic shape to similar walls with plywood panels. The results presented in Table 2.1 show that the normalized energy dissipation is almost the same for OSB and plywood (DFP, CSP) panels.

Considering the points mentioned in 2.1.1. to 2.1.3., it can be expected that by identifying a thin hysteretic loop that is calibrated to match the experimental results, a conservative equivalent viscous damping expression for design purposes can be achieved. It can be expected that a single EVD expression will be suitable for EVD of the walls of any length or number, fastener spacing, steel properties and sheathing type, provided that the sheathing type is not very different in terms of hysteresis shape and displacement capacity than those studied here. Furthermore, by selecting a fat hysteresis loop among the tests that have different sheathings of OSB, CSP and DFP, and by determining the corresponding EVD, an upper limit to the EVD can also be gauged.

In line with the above, and considering the normalized energy dissipation reported in Table 2.1, the experimental test no.s 14 and 4 are selected to represent thin and fat hysteretic loops respectively. Boudreault (2005) calibrated the parameters of the Stewart hysteresis model (see Fig. 2.1) for a range of experimental test conducted in McGill University (see Fig. 2.2.).



FU	Ultimate force or moment	(> 0.0)
FI	Intercept force or moment	(> 0.0)
PTRI	Tri-linear factor beyond ultimate force or moment	
PUNL	Unloading stiffness factor	(> 1.0)
GAP+	Initial slackness, positive axis	(> 0.0)
GAP-	Initial slackness, negative axis	(< 0.0)
BETA	Beta or Softening factor	(≥ 1.0)
ALPHA	Reloading or Pinch power factor	(≤ 1.0)

Figure 2.1. Stewart hysteresis model (Carr, (2009))

These calibrated parameters are used in this study to set the spring characteristics of the selected hysteresis loops for elements used in the SDOF model to determine the EVD of CFSFWP shear walls. Some parameters are highlighted in Fig. 2.2. Using these parameters, the hysteresis shape of a CFSFWP shear wall corresponding to the wall configuration of the selected experimental test can be formed, regardless of the length of the wall, which will affect the strength parameters of the Stewart model. In other words, by using the highlighted parameters (r, F_u/F_y, P_{tri}, F_i/F_y, P_{UNL}, β and α) it is possible to define a SDOF model with wall characteristics of the experimental test and a desired level of strength and stiffness.

Group	Wood Panel	Size	Srew Pattern	K_0 (kN/mm)	r	Fy (kN)	Fy (kN)	Fu/Fy	Fu (kN)	Fi (kN)	P_{Tri}	Fi/Fy	P_{UNL}	β	α
16	CSP	2'x8'	6"x12"	0.33	0.26	3.70	-3.70	1.81	6.70	0.65	0	0.18	2.00	1.10	0.41
18	CSP	2'x8'	4"x12"	0.40	0.25	5.50	-5.50	1.79	9.86	1.00	0	0.18	2.40	1.10	0.35
8	CSP	4'x8'	6"x12"	1.15	0.20	9.20	-9.20	1.50	13.83	1.50	0	0.16	1.65	1.10	0.41
4	CSP	4'x8'	4"x12"	1.05	0.25	12.45	-12.45	1.50	18.70	1.75	0	0.14	2.20	1.10	0.35
10	CSP	4'x8'	3"x12"	1.50	0.23	20.45	-20.45	1.50	30.70	2.25	0	0.11	1.65	1.09	0.23
30	CSP	8'x8'	6"x12"	2.20	0.18	21.50	-21.50	1.46	31.30	2.70	0	0.13	2.25	1.10	0.41
32	CSP	8'x8'	4"x12"	2.40	0.30	28.50	-28.50	1.63	46.40	3.90	0	0.14	2.10	1.09	0.25
34	CSP	8'x8'	3"x12"	3.20	0.30	37.00	-37.00	1.71	63.30	4.45	0	0.12	1.70	1.07	0.27
12	DFP	4'x8'	6"x12"	1.25	0.16	11.00	-11.00	1.55	17.10	1.00	0	0.09	2.20	1.10	0.41
6	DFP	4'x8'	4"x12"	1.55	0.20	15.50	-15.50	1.65	25.50	2.50	0	0.16	1.55	1.10	0.35
14	DFP	4'x8'	3"x12"	1.75	0.26	22.00	-22.00	1.65	36.20	3.00	0	0.14	1.55	1.09	0.23
20	OSB	2'x8'	6"x12"	0.40	0.28	3.50	-3.50	1.86	6.50	0.65	0	0.19	2.40	1.10	0.41
28	OSB	2'x8'	4"x12"	0.57	0.22	6.40	-6.40	1.58	10.12	1.00	0	0.16	1.80	1.10	0.45
22	OSB	4'x8'	6"x12"	1.60	0.20	8.40	-8.40	1.61	13.50	1.00	0	0.12	1.75	1.10	0.45
24	OSB	4'x8'	4"x12"	2.10	0.23	13.40	-13.40	1.49	20.00	1.40	0	0.10	1.75	1.10	0.45
26	OSB	4'x8'	3"x12"	3.00	0.22	17.00	-17.00	1.68	28.50	2.50	0	0.15	1.25	1.10	0.45

Figure 2.2. Stewart hysteresis model parameters (after Boudreault ,2005).

2.2. Procedure for Determining the EVD

Initially the wall system is defined as a SDOF system using a nonlinear spring with characteristics adopted based on the desired shape of the hysteresis model, obtained from experimental tests, and the characteristics of the system (T_e and m_e). The methodology used to determine the equivalent viscous damping for a substitute SDOF structure with effective mass m_e, an effective period Te and for displacement ductility demand equal to μ is described in Fig. 2.3.

By assuming a yield displacement, Δ_y, the maximum displacement, Δ_{max}, for the target ductility value can be determined. The effective stiffness, K_e, can also be calculated using the system effective mass and period, as per Eqn. 2.2., and the maximum force can be determined from Eqn. 2.3.:

$$K_e = 4\pi^2 * \frac{m_e}{{T_e}^2} \quad (2.2)$$

$$F_{max} = K_e . \Delta_{Max} \quad (2.3)$$

Depending on whether the target displacement Δ_{Max} is greater or less than the displacement at which the ultimate strength is first attained (point B of Fig. 2.4.) F_u and then F_y can be determined using Eqn. 2.4. and Eqn. 2.5. respectively:

$$F_u = \begin{cases} F_{Max} & \Delta_{Max} > \Delta_b \\ \gamma \frac{F_{Max}}{1+r(\mu-1)} & \Delta_{Max} \leq \Delta_b \end{cases} \quad (2.4)$$

$$F_y = F_u/\gamma_1 \quad (2.5)$$

where the displacement corresponding to point B, Δ_b, is determined from Eqn. 2.6., by setting the ratio of $\gamma_1 = F_u/F_y$ and r from the calibrated parameters of the hysteresis shape.

$$\Delta_b = \left[1 + \frac{\gamma_1 - 1}{r}\right] . \Delta_y \quad (2.6)$$

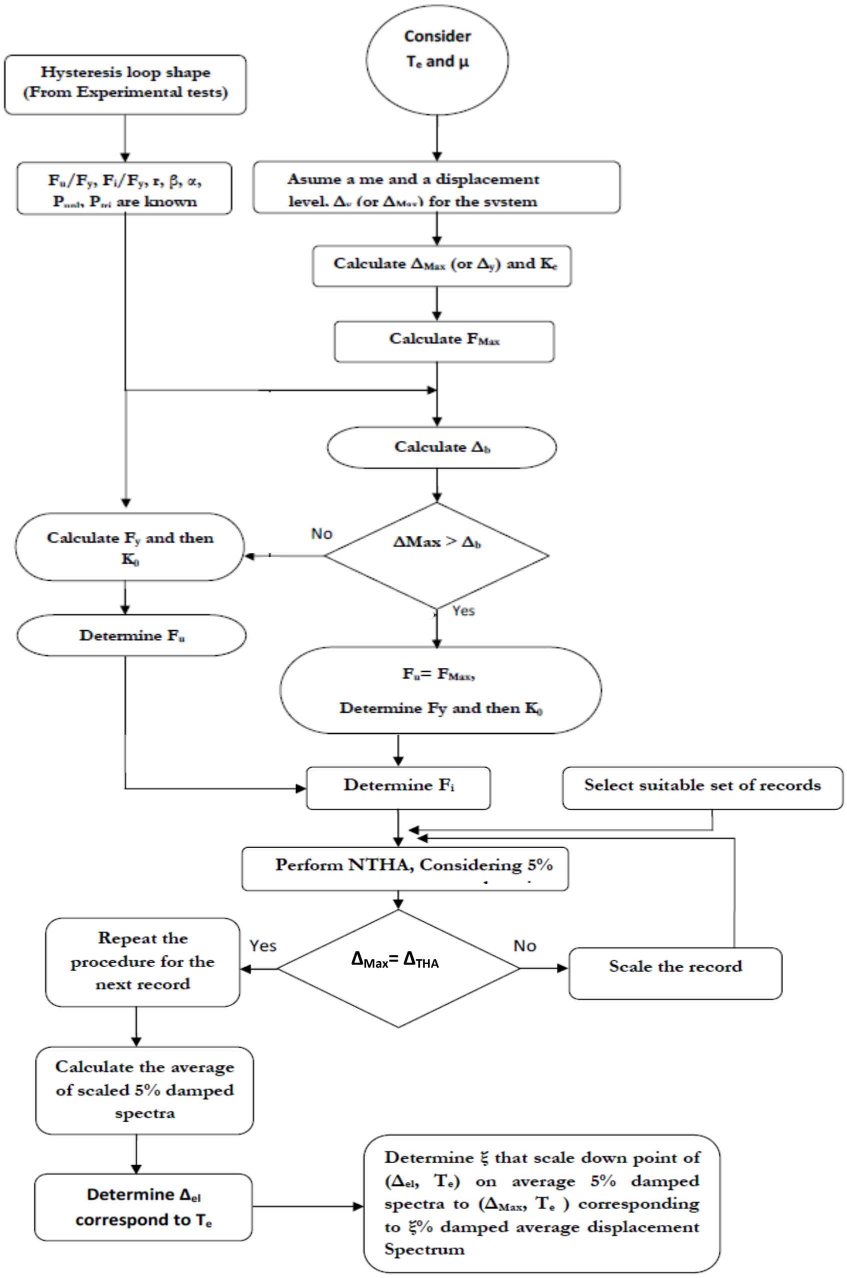


Figure 2.3. Methodology used for determining the EVD (from Moyaed Alaee et al., 2012).

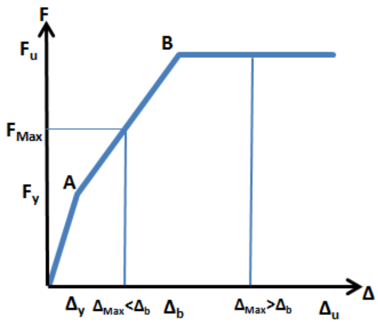


Figure 2.4. Stewart model backbone - Parameter definition (from Moayed Alaee et al., 2012)

Having determined all the parameters of the nonlinear spring, NLTH analyses are performed on the SDOF system using accelerograms scaled so that the maximum recorded inelastic displacement equals the assumed (target) displacement (Δ_{Max}), for the target displacement ductility demand. The scale factors are then applied to the displacement spectra of the corresponding records and the average of the scaled spectra is determined. Hence, the elastic displacement, Δ_{el}, corresponding to the effective period, T_e, can be read from the average spectra. The damping that causes the elastic spectral displacement response, Δ_{el}, to reduce to the inelastic displacement response of the SDOF system (i.e. the damping that gives $\Delta_{el} = \Delta_{Max}$) is determined by calculating the damping that corresponds to a reduction factor equal to $\eta = \Delta_{in}/\Delta_{el}$, where an appropriate means of scaling elastic spectra to different damping levels is required (see Pennucci et al. 2011). This process gives a single EVD data point for a given hysteretic shape, ductility demand and effective period. In order to develop expressions for the EVD, the procedure should be repeated for other values of displacement ductility and period.

In order to run the NLTH analyses, the program Ruaumoko (Carr, 2009) is used. The parameters of the Stewart model were calibrated using the selected hysteresis loops (thin and fat as explained in section 2.1) and the described procedure in Fig. 2.3. The elastic damping is considered equal to 5% of critical damping in the models. Taking into account the considerable presence of non-structural elements in CFSFWP shear wall structures, 5% elastic damping is considered reasonable. It is important to select an appropriate damping model for correct application of the methodology. The damping force depends on the value of the adopted stiffness. As recommended by different researchers (see Priestley et al. 2007), adopting initial stiffness-proportional elastic damping results in large and spurious elastic damping forces when the response is inelastic. As such, it is recommended that for modern buildings with lightweight non-structural elements, elastic damping should be modelled by tangent stiffness proportional damping. As such, a tangent stiffness-proportional damping model (ICTYPE 6) was used in Ruaumoko, where the damping coefficient is proportionally changed with the stiffness to provide a reduction in damping force as the structural stiffness softens.

2.2. EVD Expressions for the Direct DBD of CFSFWP Shear Wall Systems

The EVD values obtained using the procedure described in the previous section for the Thin hysteretic model are presented in Fig 2.5. It can be seen that the EVD increases with ductility demand and it can also be seen that the EVD is relatively independent of the effective period. In Fig. 2.6 the average of the EVD determined for different periods of vibration is compared for the Thin and Fat models. It is apparent that at low ductility demands the EVD is the same and at ductility demands greater than 2.0 the Fat model provides higher damping values. The maximum difference between the two models occurs at ductility of 4, where the equivalent viscous damping ratio for the Thin Model is 15.6%, and for the Fat Model is 19.3% ratio. These EVD values would predict peak inelastic displacement demands that differ by only 10%. Therefore, if an expression is adopted based on the Thin Model, it is assumed that the amount of error is still in an acceptable range for the fat model and would be conservative.

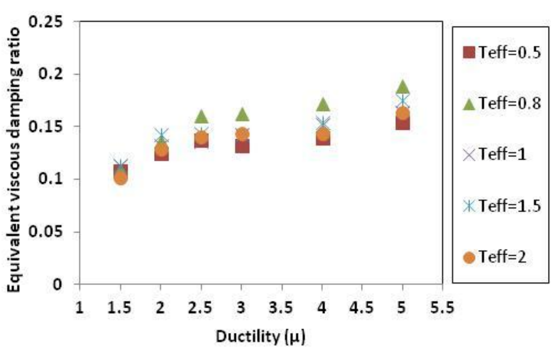


Figure 2.5. EVD of CFSFWP shear wall, Thin Model

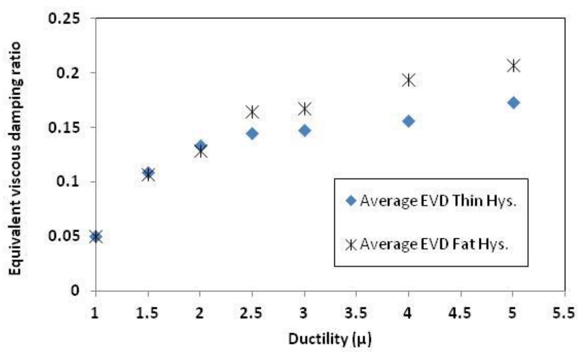


Figure 2.6. Difference between the average EVD of Fat and Thin models

Aiming to propose an expression in similar format of those proposed by Priestley et al. (2007), a curve was fitted to the Thin Model's EVD data by minimizing the error on the whole range of ductility. The proposed equation is:

$$\xi_e = 0.05 + 0.478\frac{(\mu-1)}{\mu\pi} \tag{2.7}$$

In Fig. 2.7 the result of the proposed equation is compared with the EVD curve of the Thin Model.

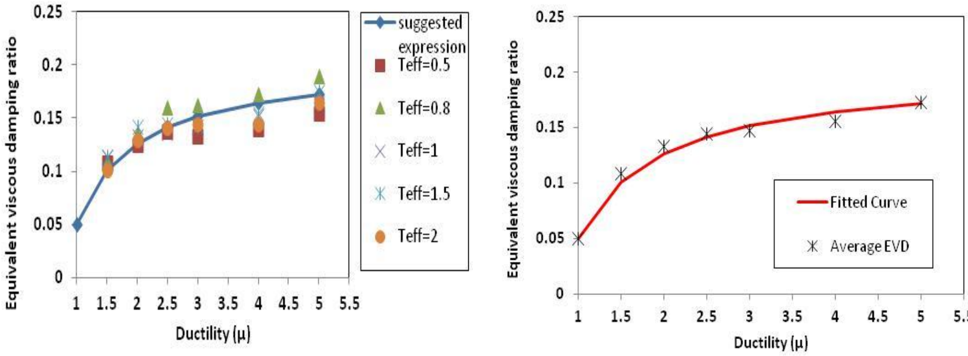


Figure.2.7 Comparison of fitted EVD curve and the mean values of EVD of different periods

To propose an expression for DDBD approach, which require less trial and error, Eqn. 2.8. is also proposed:

$$\xi_e = \begin{cases} 0.095\mu - 0.045 & if\ 1 \le \mu \le 2 \\ 0.145 & if\ \mu > 2 \end{cases} \tag{2.8}$$

The proposed curve is shown in Fig. 2.8.

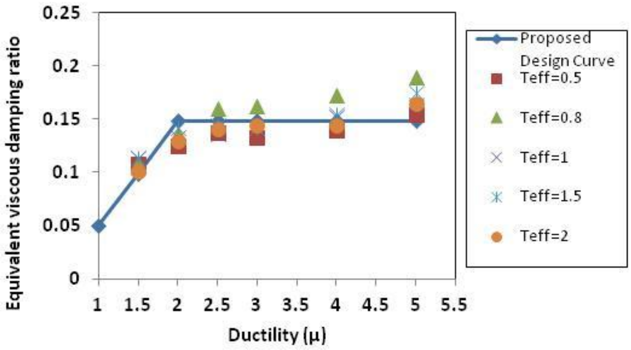


Figure 2.8. Proposed EVD for DDBD procedure

To eliminate problems associated with the use of scaling expressions for highly damped elastic spectra, Pennucci et al. (2011) proposed the use of ductility-dependent displacement reduction expressions that directly indicate the ratio of the peak inelastic displacement obtained from NLTH analyses to the elastic displacement obtained from the average of the elastic displacement spectra of a set of records at the effective period of the model, Δ_{in}/Δ_{el}. In this way, without incorporating any specific damping modifier equation, a scaled inelastic spectrum associated with effective period can be obtained, without determining the EVD. Displacement reduction factors have consequently been determined from the results of NLTH analyses and are demonstrated in Fig. 2.9. Eqn. 2.9. demonstrates the proposed ductility reduction factor expression for CFSFWP shear walls.

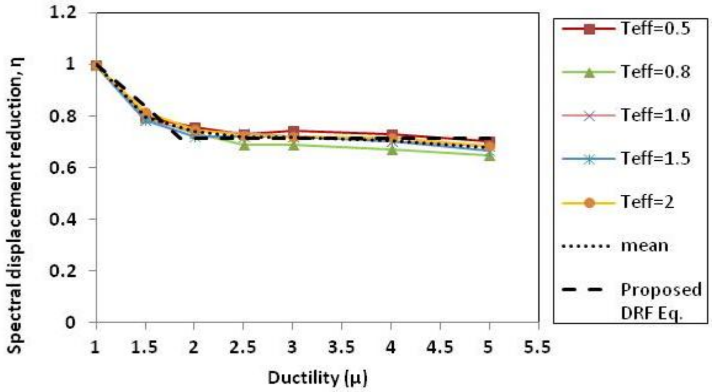


Figure 2.9. Comparison of the proposed ductility reduction factor expression with the analysis results

$$\eta = \begin{cases} -0.32\,\mu + 1.32 & if\ \mu \le 1.9 \\ 0.71 & if\ \mu > 1.9 \end{cases} \tag{2.9}$$

3. DISPLACEMENT PROFILE FOR DDBD OF CFSFWP SHEAR WALL SYSTEMS

In the DDBD of MDOF systems, a design displacement profile is required in order to transform the MDOF system into an equivalent SDOF system. It depends on an assumed displacement shape of the structure and the limit state displacement or drift of the most critical member of the real structure. The displacement shape corresponds to the inelastic first-mode at the design level of seismic excitation. Often, the elastic and inelastic first-mode shapes are very similar. In CFSFWP shear walls with platform framing, the shear walls are disconnected in each floor from the top and bottom walls. As it was observed in different experimental tests, these walls deform into a parallelogram under lateral loading and clearly demonstrate shear type behaviour. Considering this, it would be a reasonable choice to consider a linear profile for the displacement shape ($\delta_i = H_i/H_n$), particularly knowing that these structural systems are not used in midrise and high-rise buildings (allowed only for low-rise buildings).

The assumption of a linear displacement profile is verified elsewhere in Moayed Alaee (2011) by conducting NLTHA of the designed structures, as part of the verification of the design procedure. By assuming the displacement shape as known, the design displacement, the effective mass and the equivalent viscous damping can be determined and as is shown in Moayed Alaee (2011) the proposed DDBD procedure has been able to rationally design the CFSFWP shear wall structures. The mean interstory drifts obtained from NLTHA responses of a 3-story building (designed with the proposed DDBD procedure using the proposed EVD expression and the displacement profile) to 10 selected earthquake records is compared with design drifts as illustrated in Fig. 3.1.

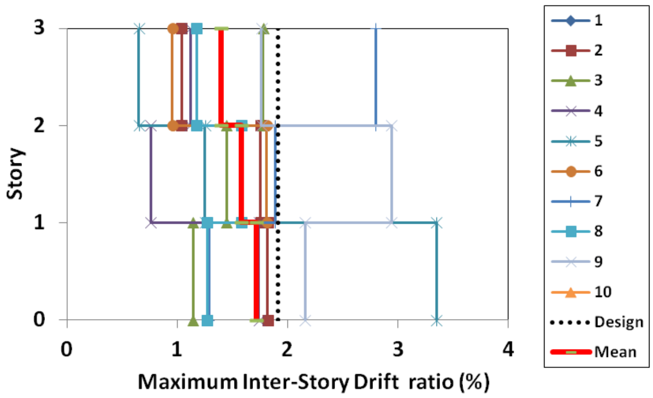


Figure 3.1. Maximum Interstory drift of a 3-story building for 10 selected records and comparison of mean of interstory drifts with design value

4. CONCLUSIONS

A new equivalent viscous damping expression and displacement reduction expression were proposed to be used in direct displacement based design of the cold-formed steel frame/wood panel shear wall systems.
Use of the proposed expressions in the proposed DDBD procedure, in which a linear displacement profile is assumed, is proved to lead to a rational design of a case study 3-story CFSFWP shear wall structure.

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