IMPLEMENTATION OF ADVANCED FLAG-SHAPE (AFS) SYSTEMS FOR MOMENT-RESISTING FRAME STRUCTURES

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ABSTRACT :

A second generation of self-centering/dissipating systems, referred to as Advanced Flag-Shape (AFS) systems, has been recently proposed by the authors, consisting of combination of alternative forms of energy dissipation (yielding, friction or viscous damping) in series and/or in parallel with re-centering elements to achieve high seismic performance for both far-fault and near-fault motions. In particular, the unique properties of a system combining friction dampers in series with viscous dampers, then combined in parallel with re-centering and hysteretic dissipation elements, was found to lead to an enhanced, predictable and controllable performance of single-degree-of -freedom (SDOF) systems. In this contribution, after a brief introduction on the concept of the AFS systems, the extension of the concept from SDOF to MDOF frames systems is discussed and numerically investigated. Two critical issues of extending AFS for SDOF systems to MDOF frame systems are briefly discussed: a) the excitation velocities up the structure b) the global frame damping capacity within DDBD design. With reference to a set of frame systems, initially designed for self-centering un-bonded post-tensioned precast concrete frames using Direct Displacement-Based Design (DDBD), the seismic performance of AFS frames in comparison to conventional frames is investigated by means of non-linear time-history analyses using a suite of far field and near-fault earthquake excitations, where three key global response parameters are examined.

KEYWORDS: Self-centering, advanced flag-shape, frame system, near-fault response, added damping

1. INTRODUCTION

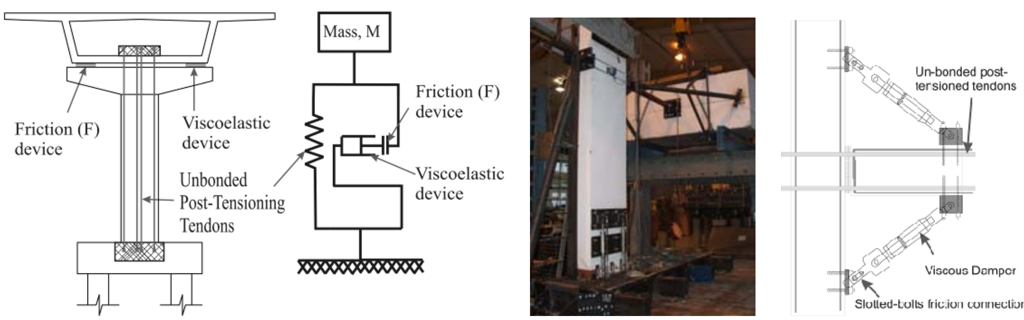
Increased public awareness in seismic engineering demands for higher predictability, reliability and performance in terms of structural behaviour under strong seismic excitation, leading to the development of the Performance-based Earthquake Engineering (PBEE). In the search of alternative new seismic-resisting systems that would perform according to the higher performance objectives set within PBEE, structural systems with the emphasis on minimising damage and financial losses have been developed. In particular, "controlled rocking" system, where un-bonded post-tensioned tendons are used in conjunction with hysteretic energy dissipations to achieve self-centering capacity and negligible structural damage and residual deformation, has been a major development in seismic engineering research. This innovative lateral resisting system, exhibiting a flag-shape hysteretic behaviour, has been thoroughly tested experimentally and numerically for various building materials (precast concrete, steel and timber) (Christopoulos et al., 2002; Palermo et al., 2005; Priestley et al., 1999), and also extended to design code provisions and guidelines (NZS3101, 2006). In addition, investigations have been carried out on the feasibility of combining re-centering systems with viscous damping (Kurama, 2001) or friction energy dissipation devices (Morgen and Kurama, 2004).

As more strong ground-motions are recorded within near-fault urban areas, the peculiar nature of ground motions with directivity and fling-effects (Somerville et al., 1997) and structural responses under these near-source events (Alavi and Krawinkler, 2004) have gained much attention amongst practitioners and researchers. Studies have shown that well-designed conventional monolithic structures can be subjected to higher-than-expected displacement and ductility demand under near-fault excitation, particularly for moderate to long period frame structures. Preliminary studies on near-fault effects on SDOF flag-shaped hysteresis systems have indicated a similar, though less pronounced, sensitivity of such systems, when the dissipation capacity is relied upon hysteretic damping (Kam et al., 2007). Following research recommendation for base-isolation (Makris and Chang, 2000) and (Kasai and Minato, 2005), it has been suggested (Kam et al., 2006) that a combination of viscous (velocity-dependent) and hysteretic (friction or yielding-hysteresis) energy dissipation, in parallel with self-centering elements (un-bonded post-tensioned tendons) can provide a superior performance in terms of controlling peak displacement, base shear and floor acceleration, in regardless of the type of earthquake ground motion (far field or near field). These systems have been named Advanced Flag Shape systems, AFS.

In this paper, as a part of a larger experimental-analytical investigation on the use of advanced seismic resisting system ongoing at the University of Canterbury, the concept of AFS is extended to multi-degree-of-freedom (MDOF) structures, in particular moment-resisting frames. The critical aspects associated with the application to MDOF are briefly discussed, in particular within the context of the Direct Displacement-Based Design approach (DDBD) (Priestley et al., 2007). Using three case-study prototypes: five-, ten- and fifteen-storey moment frames, subjected to non-linear time history analyses, the paper attempts to address the effectiveness of the AFS MDOF systems.

2. ADVANCED FLAG SHAPE (AFS) SDOF SYSTEMS

Herein, a brief description of the concept of Advanced Flag-Shaped (AFS) systems and a summary of the previous SDOF study conclusions are presented. More details can be found in (Kam et al., 2006; Kam et al., 2007). The AFS is a further evolution of the re-centering structural systems' family. Instead of relying on a single-type of hysteretic energy dissipation, the AFS systems advocate a combination of alternative forms of energy dissipation in parallel and in series with re-centering elements (such as un-bonded post-tensioned tendons). Figure 1 shows some illustrations of possible practical application of AFS systems and the first experimental validation of the AFS system (un-bonded post-tensioned wall systems with hysteretic and viscous dampers in parallel) under dynamic shaking table tests on (Marriott et al., 2008).



(a) (b) (c) (d)

Figure 1 a) AFS Bridge Pier b) Schematic spring-mass SDOF model c) Shake table testing of AFS Structural Wall (Marriott et al., 2008) d) AFS Beam-column Joint

In principle, there is a myriad of possible combinations of energy dissipation, but only few would be cost-effective for practical application. Figure 2 presents several possible combinations of AFS systems that have been previously studied (Kam et al., 2006). Figure 2a presents the [BLEV: bi-linear elastic spring with viscous dashpot] system, where a self-centering element is combined in parallel to viscous or visco-elastic dampers. With added viscous damping, the BLEV system is efficient in controlling the peak responses but, due to its velocity-dependent damping, it is not very effective under low-velocity excitation, typical of far-field earthquakes. In order to overcome that, a combination of viscous dampers and hysteretic dampers in parallel with self-centering elements has been proposed as [AFS1] system, as shown in Figure 2b. While this system has the advantage of adequate energy dissipation under both near-fault (high velocity pulse) earthquakes and far-field (lower velocity content) earthquakes, AFS1, as well as BLEV, systems risk developing excessive forces in the event of high excitation velocity, due to the velocity-dependent dampers. This can be resolved by combining in series, the viscous or visco-elastic dampers with a friction slip element or by using highly non-linear viscous dampers (high power factor), where the peak force generated by the viscous dampers can be controlled to a pre-determined level. This concept is similar to the VEP (visco-elasto-plastic) braces developed in Japan (Kasai and Minato, 2005). [AFS2] system is then a simple modification of the basic AFS1 system, where friction slip element is added to control the viscous damping forces, as shown in Figure 2c. Numerical studies on the response of SDOF AFS systems, when compared to conventional systems [modeled by simple bi-linear elasto-plastic hysteresis - BL] and self-centering flag-shape hysteresis system [FS], have shown the efficacy of implementing a combination of velocity-proportional and displacement-proportional energy dissipation. Figure 2d presents an example of force-displacement responses of 2 AFS SDOF systems (BLEV and AFS2) and two conventional SDOF systems (BL and FS), where all systems are designed for the same monotonic capacity backbone curve.

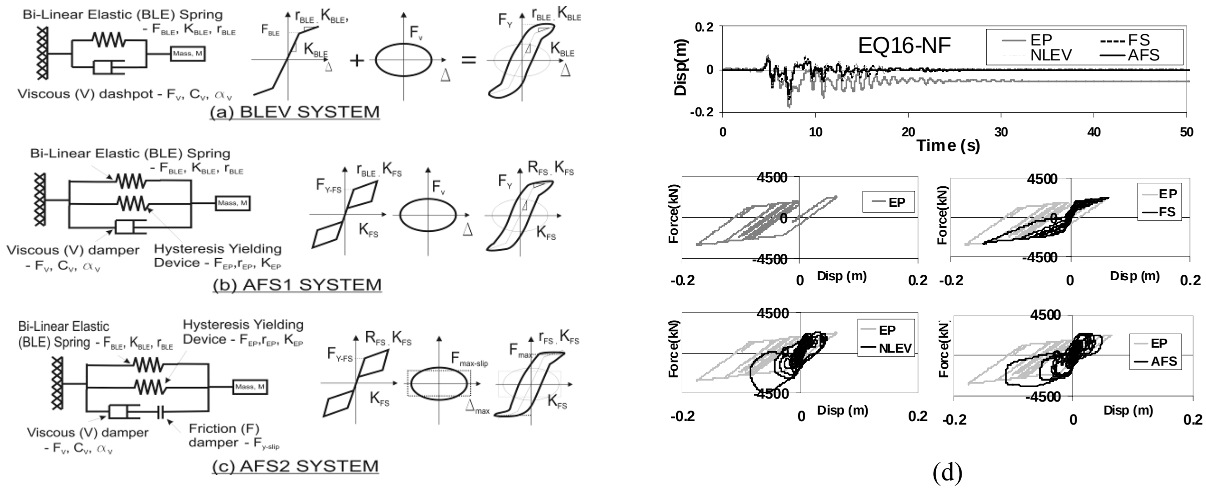


Figure 2 (Left): Rotational Spring Models and Hysteresis Models of Advanced Flag-Shape Systems :(from top) a) BLEV Systems b) AFS1 Systems c) AFS2 Systems; (Right) d) Example of non-linear time-history and force-displacement responses of 4 SDOF systems under near-fault earthquake (Gebze Station, Kocaeli, Turkey 1999 earthquake) (Kam et al., 2007)

From Figure 2d, the superior performance of AFS systems (BLEV and AFS2) is evident: the friction slip element limits the viscous damping forces, while minimizing the displacement response. Adequate energy dissipation was generated in low-cycle high velocity near-fault events through the use of velocity-dependent energy dissipation. The BLEV system, while developing higher damping capacity when subjected to a high velocity excitation (i.e. near-fault event), has a significantly higher base shear demand, due to the high viscous damping force. On the other hand, the use of friction dampers in series with viscous/visco-elastic dampers in AFS2 allows for direct control of the velocity-dependent damping forces. There are negligible residual deformations in all the self-centering system with controlled-rocking technology. Lastly, damaged energy dissipaters are replaceable and the overall control system is of low maintenance.

3. EXTENSION TO MDOF FRAME SYSTEMS

Readers are referred to previous publication by the authors (Kam et al., 2008) on the critical design issues and procedure for AFS MDOF frame systems. Herein, only two critical aspects of the extension of the system to MDOF are briefly discussed: (a) the effectiveness of velocity-dependent devices, placed at the rocking interface of the beam-column joints of a moment-resisting frame system (b) the estimation of the viscous damping of the equivalent SDOF system for design. It is noted that amplification factor for higher mode and P-Δ effects can be critical to the design of AFS MDOF structures.

3.1 Induced velocities on velocity-dependent energy dissipation devices

For moment-resisting frames, it is assumed that the velocity-dependent energy dissipation devices (viscous or visco-elastic dampers) will be placed at the beam-column joint interface, to take advantage of the opening and closing of the gap during the rocking motion, as shown in Figure 1c. Therefore, the induced velocities are expected to vary along the storey height as the rate of beam-column interface gap rotation rate varies up the structure due to the geometry and response of the structure. Intuitively, the variation of induced velocities up to a MDOF structure follows the induced floor acceleration, depending on the structure's dynamic properties. Considering the dampers acting in the gap opening rocking interface, the induced velocity on the dampers can be approximated with a non-linear distribution along the height of the building, depending on the building geometry and characteristics. A set of equations to approximate the design damper velocity, as a function of the design spectral velocity (depending on effective period) and the location up the building height is given in (Kam et al., 2008). Alternatively, according to the (FEMA-450, 2004), the design displacement, Δ_D and the effective period, $T_{1D}\sqrt{\mu_D}$, can be used to estimate the storey velocity (hence the damper design velocity). In FEMA-450, the effective additional equivalent damping due to the added dampers, which is derived based on energy-based methods, is used to reduce the seismic input. As an alternative approach herein presented, the added damping is taken into account directly within a DDBD framework, whereby the target displacement would dictate the required system equivalent viscous damping, ξ_{sys}, as described in the next section.

3.2 Estimation of equivalent viscous damping for DDBD design

The proposed procedure is an addendum to the state-of-the-art practice of the DDBD procedure(Priestley et al., 2007). In a DDBD procedure for frames, the influence of different structural systems on the design outcome is reflected on three key parameters: (1) the displacement shape profile (2) the yield drift associated to the yield rotation of the plastic hinge elements and (3) the viscous damping ξ_{SDOF} of the equivalent (substitute structure) SDOF system. While AFS systems should in theory have a displacement profile and 'yield' drift limit as per flag-shape hysteresis system, the derivation of the ξ_{SDOF} for AFS systems varies significantly. In estimating the ξ_{SDOF} value for AFS systems, the geometric stiffness (area-based) method, where the energy dissipated in a cycle of harmonic AFS hysteresis is equated with a linear visco-elastic system at resonance, can be used. Equation 3.1 below is derived to estimate the ξ_{SDOF} for AFS systems. Due to space limitation, the full derivation of equation is not provided here.

$$\xi_{eq,AFS} = \xi_{Elastic} + \xi_{Viscous} + \xi_{Hysteretic} = 0.05 + \frac{\lambda_2}{2(\lambda_1+1)}\beta_V S_V\{T_{Eff}\} + \frac{(1-\lambda_2)}{(\lambda_1+1)}\frac{[1+2(\mu-1)]}{\pi\mu} \tag{3.1}$$

Where μ is the structural ductility, β_V is an effective damping reduction factor (depending on the location of dampers, where for viscous dampers at beam-column joint interface, $\beta_V \approx 0.15$) and $S_V(T_{eff})$ is the velocity spectra ordinate corresponding to the effective period, T_{Eff}. λ_1 and λ_2 are design parameters proposed for AFS systems to indicate the ratio between the re-centering moment contribution and the dissipative moment contribution overall as well as the ratio between the velocity-dependent and the overall dissipation moment contribution , as given in Equations 3.2 and 3.3

$$\lambda_1 = M_{pre\text{-}stressing} / M_{dissipation} \tag{3.2}$$

$$\lambda_2 = M_{velocity\text{-}dependent\text{-}dissipation} / (M_{hysteretic\text{-}dissipation} + M_{velocity\text{-}dependent\text{-}dissipation}) \tag{3.3}$$

4. NUMERICAL ANALYSIS ON MDOF FRAME STRUCTURES

4.1 Prototype MDOF Frames Systems

Three MDOF prototype moment-resisting frames of five, ten and fifteen storey are adopted for this study. The frames consist of four bays of 7.5m and tributary floor width of 8m. DDBD was implemented for the un-bonded post-tensioned precast concrete frame systems (approximated as flag-shape hysteresis, FS system) under the design level of earthquake (a probability of exceedance of 10% in 50 years, R=1), deep or soft soil (type D according to NZS1170:5, 2004) and a peak ground acceleration of 0.4g. The properties of the frames are summarized in Table 1. Four different connection models are considered: two variants of AFS – the BLEV and the AFS2 system (henceforth abbreviated as AFS) and two established systems – BL (representing monolithic reinforced-concrete and moment-resisting steel connections) and FS (representing un-bonded post-tensioned rocking connections with hysteretic energy dissipation). The different hysteretic connections are designed for the same set of design internal forces. Considering the complexity of different sources of energy dissipation, "equal" secant stiffness to the yield and ultimate points are assumed in order to establish a yardstick of comparison between the hysteresis models. However, it is assumed that the velocity-dependent contribution is c at all displacements; while in reality, the moment contribution of the velocity-dependent elements is out-of-phase with the maximum displacement. All re-centering systems (FS, BLEV and AFS) have moment contribution ratio λ_1 of 1.2 to guarantee re-centering capacity. FS system has λ_2 of 0, BLEV system has λ_2 of 1 while the AFS system has λ_2 of 0.5 (50% viscous and50% hysteretic damping).

Table 1: Properties of the Prototype Frames

	5-storey	10-storey	15-storey
Design drift (%)	2.0%	1.5%	1.0%
Effective period (s)	2.37	2.95	2.76
Base shear (kN)	1252.3	2017	4345
Effective Mass (tonnes)	797	1838	2853
Equivalent Viscous damping (ξ_{SDOF})	11.5%	10.6%	9.2%

4.2 *Modeling assumption and ground motion records*

Two suites of seven historical strong ground motion records were used, representing both far-field (without any directivity effect) and near-fault events. All records are taken from the PEER online strong ground motion database (PEER, 2007). The scaling of the earthquake records followed the recommendations of (NZS1170, 2004) and to the DDBD design hazard spectra. The earthquake characteristics of the scaled earthquake records and the scaled acceleration spectra are presented in Figure 3. There are limited records with directivity effects that are compatible with the NZS1170:5, or with any other major codes uniform hazard spectra. Scaling near-fault records according to the recommendation of NZS1170:5 accounting for near-fault amplification were found to be a challenging exercise, whose actual validity should be the object of discussion and debate in future.

Name	Earthquake Event	Year	Mw	Station	Rclosest (km)	Soil Type	Scaling Factor	Scaled PGA (g)	Scaled PGV (cm/s)
FAR FIELD SUITE (WITHOUT DIRECTIVITY EFFECT)									
FF1	Superstition Hils	1987	6.7	Brawley	18.2	D	3.00	0.401	51.6
FF2	Northridge	1994	6.7	Canoga Park – Topanga Clan	15.8	D	1.27	0.452	40.7
FF3	Northridge	1994	6.7	LA – Hollywood Stor FF	25.5	C	2.15	0.496	39.3
FF4	Northridge	1994	6.7	N Hollywood – Coldwater Can	14.6	C	1.50	0.406	33.3
FF5	Loma Prieta	1989	6.9	Capitola	14.5	C	1.19	0.571	43.4
FF6	Landers	1992	7.3	Desert Hot Springs	23.3	D	2.09	0.320	43.7
FF7	Landers	1992	7.3	Yemo Fire Station	24.9	D	1.82	0.382	54.1
NEAR FAULT SUITE (WITH DIRECTIVITY EFFECT)									
NF1	Northridge	1994	6.7	Newhall Fire Station	5.92	D	0.53	0.312	51.4
NF2	Northridge	1994	6.7	Sylmar - Olive view Med Ctr	5.30	D	0.41	0.347	53.4
NF3	Northridge	1994	6.7	Jensen Filter Plant	7.01	C	0.43	0.180	45.1
NF4	Imperial Valley	1979	6.5	El Centro Array# 7	0.56	D	0.52	0.242	57.2
NF5	Loma Prieta	1989	6.9	Los Gatos Pres Center	3.88	B	0.38	0.211	35.6
NF6	Tabas, Iran	1978	7.4	Tabas	2	D	0.58	0.495	70.5
NF7	San Fernando	1971	6.6	Pacoima Dam Abutment	1.81	B	0.51	0.623	57.2

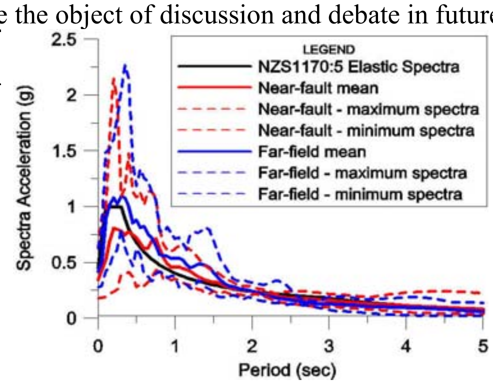


Figure 3 (left): Characteristics of the 7 Scaled Far-Field Ground Motion Records and 7 Scaled Near-Fault Ground Motions (Fault Normal Direction) (Right): acceleration spectra for the far-field and near-fault earthquake records.

The inelastic time-history analyses were performed using the finite-element program RUAUMOKO2D (Carr, 2008). Newmark-beta integration scheme with a Rayleigh damping model proportional to the tangent stiffness was adopted. P-Δ effects were ignored while lumped mass and plasticity modeling are adopted. According to capacity design principle, the inelasticity deformation is restricted to the end of beams and ground floor columns.

5. RESULTS

5.1 Average Inter-storey Drift Envelope Response

The average inter-storey drift envelopes over the ensemble of the far-field earthquakes (top row) and near-fault earthquakes (bottom row) of the five-, ten- and fifteen storey frames are shown in Figure 4. While all the conventional systems achieved the target inter-storey drift, there is some conservatism for AFS and BLEV systems, indicating higher-than-expected energy dissipation from the velocity-dependent dampers. Bearing in mind that in this study, similar monotonic capacity curve is assumed for all systems, the lower drift demands for AFS and BLEV systems would indicate that both AFS and BLEV systems can be designed for lower strength capacity. It was also observed that for taller frames (e.g. 15-storey, compared to 10-storey), the effectiveness of velocity-dependent energy dissipation decreases as the induced velocity decreases up the structure as the number of storey increases. However, it should be noted that the velocity response at each level is typically related to the inter-storey drift and floor acceleration response. Since these induced velocities affect the effectiveness of the viscous dampers, which subsequently alter the response of the frames, a distribution of induced velocity up the structure has to be assumed during the design phase. It should be noted that while AFS systems reduce the peak drift response, the base shear demand does not increase substantially, as shown in the next section.

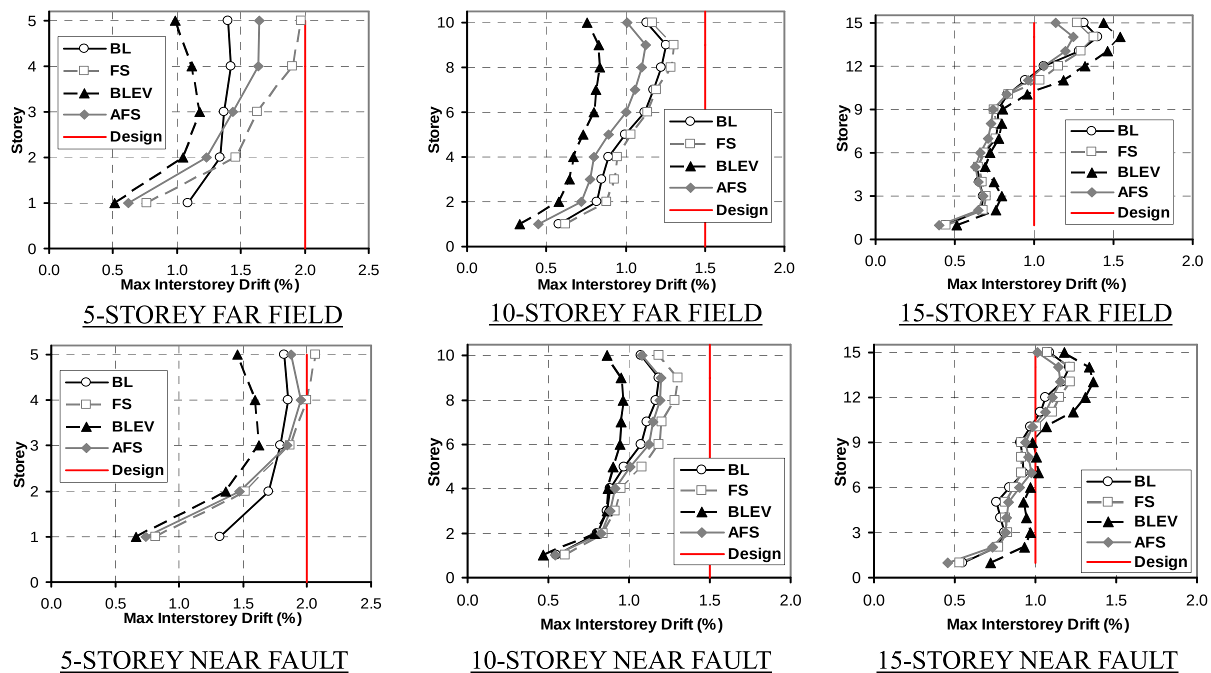


Figure 4 Mean of peak inter-storey drift envelopes of the 7 far-field earthquakes (first row) and 7 near-fault earthquakes (second row) for five-, ten- and fifteen-storey frames.

5.2 Cumulative Storey Shear Responses

Figure 5 presents the average of storey shear responses for the ten-storey frames only for both a) far-field and b) near-fault earthquakes. The shear demand is also found to be comparable to the DDBD storey shear values, where design was based on a monolithic reinforced concrete frame (BL) system. It was found that AFS system has lower storey shear and base shear demand under both types of excitations with and without directivity effect, indicating that the use of friction-slip mechanism succeeded in controlling the peak viscous damping forces. BLEV on the other hand has relatively higher base shear in the near-fault earthquakes on average, given the higher excitation velocity. For BLEV system, shear demand is often higher on upper stories, as evidently shown on Figure 5 (similar results were observed for 5- and 15-storey frames). It was also found that the base shear reduction for AFS and BLEV decreased up the height of the structure. This relates to the decrease in induced excitation velocity up the structures, as discussed in Section 3.1. This may suggest that AFS system could be effective in segmental-isolation system, where the inelastic mechanism may be concentrated at lower stories.

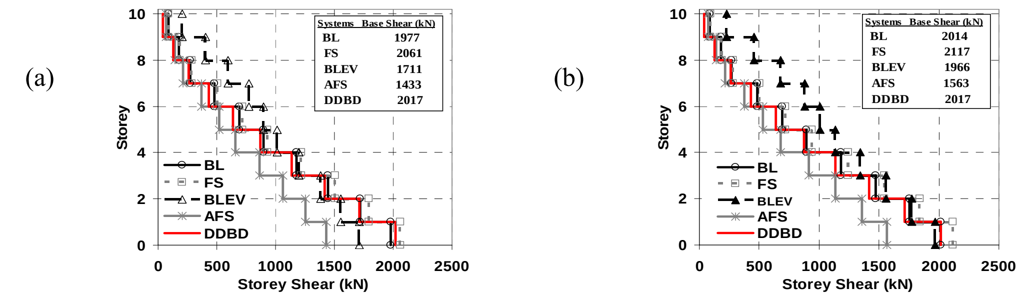


Figure 5 Mean values for cumulative storey shear for ten-storey frames under (a) far-field earthquakes and (b) near-fault earthquakes, in comparison to the DDBD cumulative beam-shear values.

5.3 Residual Deformation & Floor acceleration

Due to space limitation, residual deformation results are not presented here. All advanced-flag shape and flag-shape systems (AFS, BLEV and FS) achieved self-centering capacity, while conventional monolithic frames (BL) have significant residual deformation, which indicates large structural damage. In controlling floor acceleration, it was found that AFS and BLEV systems are more effective in controlling floor acceleration, when compared to traditional systems (BL and FS). Figure 6 below presents the results of the floor accelerations in the structures for both far-field and near-field events. For the relatively flexible prototype frames, the increasing building heights do not affect the peak floor acceleration demand. Damage State 1 (DS1) and Damage State 2 (DS2) in Figure 6 refer to the typical damage limit states of 0.25g (Slight damage) and 0.5g (moderate damage) proposed in (HAZUS-MH-MR3, 2003). In comparison to AFS and BLEV systems, the FS systems consistently have higher floor acceleration demand, owing to the stiffer nature of the FS connection (higher elastic stiffness for similar effective stiffness structure). The average floor acceleration envelope plot in Figure 5 also highlights the significant higher modes response in our prototype system, with the BLEV system particularly susceptible.

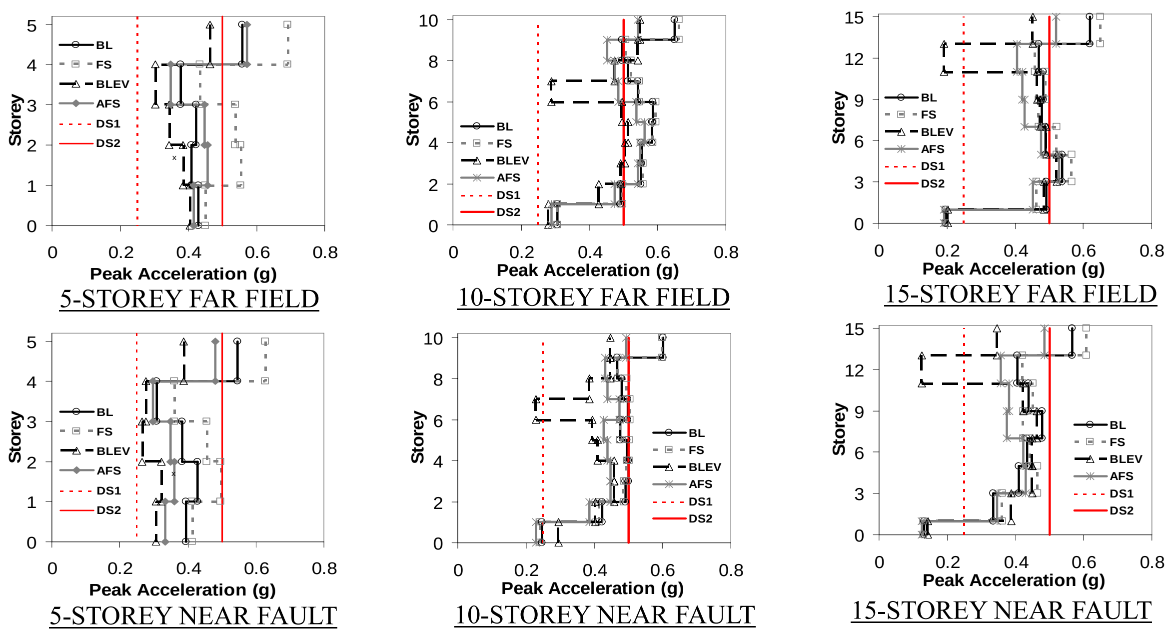


Figure 6: Average floor acceleration envelope for seven far-field earthquakes (1st row) and average floor acceleration for seven near-fault earthquakes (2nd row); DS1 = 0.2g and DS2=0.5g

6. CONCLUSIONS

This paper has presented the extension to MDOF frame systems of the concept of Advanced Flag-Shape (AFS) systems, in which alternative forms of energy dissipations (yielding, friction or viscous/visco-elastic damping) are combined in series and/or in parallel together with re-centering element to achieve a more robust seismic performance under both far field and near field earthquakes. In contrast to AFS SDOF systems, the induced excitation velocity up a MDOF structure is critical to the design of AFS MDOF systems. Basic recommendations for the DDBD of AFS MDOF systems have been given. Lastly, the results of non-linear time history analyses using a suit of far-field and near-fault earthquakes have shown the superior performance of the Advanced Flag-Shape systems (BLEV and AFS) when compared to conventional systems (BL and FS). Particularly, AFS system has improved responses without any significant increase to base shear demand. All the re-centering systems achieved negligible residual deformations, indicating minimal damage to the structural components. The advanced flag-shape systems (BLEV and AFS) also provide a better control of the floor acceleration response.

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