INTERNATIONAL JOURNAL OF
COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

IJCOE Vol.11/No. 2/Spring 2026 (72-78)

Available online at: www. Ijcoe.org

Seismic Assessment of Suspended-Zipper Braced Frame (SZBF) in Coastal Steel Structures Equipped with ADAS-SMA Hybrid Damper

[1] Ahmad Hasanpoor Ghadikolaei [1], Heydar Dashti Naserabadi [2*], Morteza Jamshidi[3]

[1)] Department of Civil Engineering, Cha. C. Islamic Azad University, Chalus, Iran. 2162633140@iau.Phd student,
[*2)] Department of Civil Engineering, Cha. C. Islamic Azad University, Chalus, Iran. dashti.n@iau.ac.ir
[3)] Department of Civil Engineering, Cha. C. Islamic Azad University, Chalus, Iran. Morteza_jamshidi@iau.ac.ir

ARTICLE INFO

Article History:
Received 30 Aug 2025
Accepted 26 Feb 2026

Keywords:
Suspended-zipper braced frames, SMA material, ADAS damper, Nonlinear static analysis, OpenSees.

ABSTRACT

In this paper, a suspended-zipper braced frame (SZBF) equipped with hybrid damper consisting of Added Damping and Stiffness (ADAS) metallic damper and shape memory alloy (SMA) wires is introduced. The proposed seismic-force-resisting system is designed by performance-based plastic design (PBPD) method, which in addition to a significant reduction in the residual displacement of the structure, can increase the collapse displacement amount by providing a suitable lateral strength and ductility compared to the conventional SZBF.
A new method for designing the proposed hybrid damper is presented, in which a factor of highest hysteretic energy is provided. The existing models in this paper are two high-rise 12 and 16-story SZBFs in two cases (a) with the conventional system and designed by force-based design method (b) with proposed hybrid damper and designed by the PBPD method. Seismic assessment of the proposed SZBF (PSZBF) by nonlinear static analysis is performed under two lateral load patterns of parabolic and uniform, in accordance with the FEMA-P695 in OpenSees software. Using the PBPD design method instead of the FBD method reduces the steel consumption by approximately 5.5-7.3% in the SZBF, which is expected to decrease further with the increasing number of stories. Since the PBPD method results in a weaker design of columns and braces than the FBD method by about 5-10%, the elastic stiffness of the PSZBF models is about 5% lower than the FBD models, that the elastic stiffness in both models can be assumed to be equal. Although PSZBF models have lower maximum lateral resistance than FBD models, they are able to absorb energy about 25% more in addition to increasing collapse lateral displacement.

1. Introduction

The bracing members, due to their high strength and stiffness, are in many structures responsible for controlling and resisting the applied lateral loads on the structure. One of the conventional types of steel bracing is the chevron bracing, which, due to its special configuration, has suitable compatibility to create architectural openings. When lateral loads are applied, at first, both bracing elements, by providing equal tensile and compressive strengths, resulting in the balancing of the lateral loads' effect.

The post-buckling strength of a compression brace according to EC8 [1], is equal to 30% of its yield strength, or its tensile strength. Also, according to the AISC [2], the post-buckling strength of a compression brace is equal to 30% of the initial buckling load of the brace. In the meantime, due to the loss of the brace compressive strength after buckling event, a large unbalanced force is created at the connection point of the braces to the beam. In this case, the seismic forces applied to the structure are concentrated in a particular story (the same story with the buckled brace). As a result, this system does not exhibit much force

redistribution capability and has not performed well in past earthquakes [3-5].
In order to achieve a stable inelastic seismic response, Khatib et al. [6] proposed adding a zipper column at the connection point of braces to the beam, in which case, along the structure height, the compressive braces buckle and the tensile braces yield. Leon and Yang [7] suggested that, if the upper story braces remain elastic, it prevents the global mechanism formation in the structure, and this modified configuration is known as an SZBF. Consequently, in the continuation of inelastic part of the capacity curve, by providing high stiffness and lateral strength, bring the structure to the target structural performance level during severe earthquakes. Despite the extensive numerical and experimental researches about the structural performance evaluation of the SZBFs in recent years [8-11], which were carried out by many researchers in order to improve the dynamic response of this type of system, we can point out some weaknesses in this system, which, in particular circumstances, removes it from an ideal seismic-force-resisting system. These weaknesses are referred to as below.
The zipper elements should be designed to transfer all unbalanced forces to the roof story, so, the size of the elastic hat members (two braces zipper column) becomes very large. If the SZBF is used in high-rise steel frames, the seismic demand for elastic hat members will be very large, therefore there is a need for large sections for them that could lead to problems such as implementation incompatibility with column and beam members with smaller sections in the roof story.
Although the SZBF with high energy absorption capacity results in minimum damage to the structural and non-structural system under moderate to severe earthquakes, it is often accompanied by large residual displacement after the earthquake that makes it unsuitable for confronting future earthquakes. Recent researches suggest that for a residual displacement ratio of more than 0.5%, building a new structure is more desirable than rebuilding or repairing a damaged structure [12]. Hence, the development of new devices without the mentioned limits requires the use of new materials. In this paper, the SZBF equipped with hybrid damper consisting of ADAS metallic yielding damper and SMA wires is introduced to deal with severe earthquakes. This proposed structural system in addition to having all the advantages of a conventional SZBF has two distinct characteristics of high recentering and high energy dissipating due to the of the super-elastic SMA material and the yielding of the ADAS damper steel strips, which is designed by considering the yielding mechanism and target drift.

2. Methods

The models' elevation is shown in Figure 1. The seismic-force-resisting system of these frames is a concentrically braced steel frame of a suspended zipper-type with special ductility. The models used in this paper are introduced in two cases. The first case models with the names of 12st-FBD and 16st-FBD are designed by the FBD method. The second case models with the names of 12st-PSZBF and 16st-PSZBF, which are designed according to the PBPD method, are equipped with the proposed hybrid damper in all zipper columns and the roof story braces. The design seismic level is life safety (LS) in accordance with ASCE7-16 standard [13].

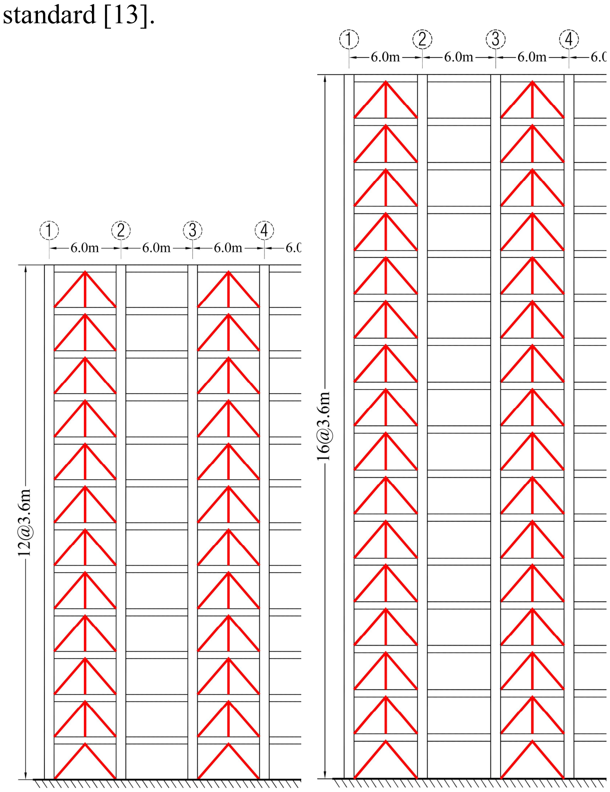
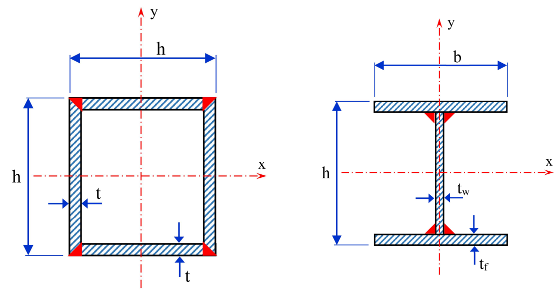


Figure 1. Elevations of models used in this paper

The steel elements of the models were designed in accordance with the AISC360-10 and IBC2006 codes [14, 15]. In the present study, the structural steel in the ADAS steel strips, SS400 grade according to the JIS G3101 standard, with yield stress, ultimate stress and modulus of elasticity are respectively equal to F_y = 308.5MPa, F_u = 446.5MPa, and E_s = 200GPa. Other steel elements of the SZBF are the A36 grade according to ASTM A36 / A36M standard, with F_y = 250MPa, F_u = 400MPa, and E_s = 200GPa. The frame mass in accordance with the ASCE41-06 standard [16] is equal to 3221 kN/Floor. The steel frames sections are shown in Figure 2. Table 1 shows the cross-section's specifications used for steel elements.



(a)	(b)

Figure 2. Cross-sections of Structural Components for, (a) Column, Zipper, and Braces, (b) Beams

Table 1. Specifications of the Cross-Sections

Column, Brace and Zipper Sections									Beam Sections				
Sections	h (mm)	t (mm)	Sections	h (mm)	t (mm)	Sections	h (mm)	t (mm)	Sections	h (mm)	b (mm)	t_w (mm)	t_f (mm)
C1	140	8	C12	375	22	C23	625	40	B1	325	175	8	10
C2	150	10	C13	400	24	C24	675	40	B2	350	200	8	10
C3	175	10	C14	425	25	C25	725	40	B3	350	200	8	12
C4	175	12	C15	450	26	C26	775	40	B4	350	200	8	15
C5	200	12	C16	475	28	C27	800	42	B5	375	200	8	15
C6	225	13	C17	500	30	C28	800	45	B6	400	225	8	15
C7	250	15	C18	525	30	C29	800	48	B7	425	250	8	17.5
C8	275	17	C19	550	32	C30	825	50					
C9	300	18	C20	550	35	C31	900	52					
C10	325	20	C21	550	40	C32	900	60					
C11	350	20	C22	600	40								

NONLINEAR STATIC ANALYSIS (PUSHOVER ANALYSIS)

In this section, the seismic behavior of SZBFs under nonlinear static analysis in two modes: (1) the SZBF designed by conventional FBD method; (2) the SZBF with SMA-ADAS damper designed by PBPD method is discussed. In order to evaluate the seismic performance of the sample frames and determine the seismic design parameter (Ω_0) of the seismic-force-resisting system under study, FEMA-P695 methodology [17] has been used. According to FEMA-P695 methodology, the structure under analysis should be affected by the combination of a gravity load of 1.05D + 0.25L where D is dead load and L is live load. The basis of loading according to FEMA-P695 methodology is based on ASCE/SEI41-06 specifications [18].

In nonlinear static analysis, earthquake lateral loads are applied statically and incrementally to structure until the displacement at a specific point (center of roof diaphragm) is reached to a target displacement or resulted in a collapse of the structure. The lateral load distribution on the structural model should be as similar as possible to what would occur during an earthquake and create critical states of deformation and internal forces in the members. The distribution is proportional to the lateral load distribution in the nonlinear static method according to the relationship of the design lateral load distribution along the building height. The fundamental period of the 12- and 16-story models is respectively 1.143 and 1.438 seconds. Two types of uniform and parabolic lateral load patterns are used to perform nonlinear static analysis. The parabolic lateral load pattern for nonlinear static analysis is according to Eq. 1.

$$F_i = \frac{w_i {h_i}^k}{\sum_{j=1}^{n} w_j {h_j}^k} \;;$$

$$K = \begin{cases} 1 & T < 0.5 \\ 0.5T + 0.75 & 0.5 \leq T \leq 2.5 \\ 2 & T > 2.5 \end{cases} \qquad (1)$$

Where F_i is the load contribution of the base shear in the i-th story, w_i is the seismic weight of the i-th story, and h_i is the height from the seismic base level to the i-th story level. The structure pushing continues as long as either the structure has reached to the general instability or during the pushing process, one or more of its members has reached to a certain limit state (e.g. Shear failure and instability in the columns). The second state of instability, which is essentially a force-based control, is termed as " Non-Simulated Collapse Modes" and needs to be controlled separately for the critical components of the structure according to their ultimate capacity. In the models of this paper, basically the structures pushing is continued to the general instability of the structure and no effect of " Non-Simulated Collapse Modes" is observed.

Normalized base shear curves based on the seismic weight versus roof displacement for the models derived from nonlinear static analysis are shown in Figure 3. The elastic stiffness of the PSZBF models is about 5% lower than that of the FBD models, due to the weaker structural elements design of the PSZBF models because of the lower base shear obtained by the PBPD method. As a result, the elastic stiffness parameter for the two types of zipper bracing FBD and PSZBF are equal with a slight difference. Another important structural parameter in pushover analysis is the energy absorption in the structure that is equal to the area under the pushover curve, and the greater this area, the structure is able to absorb more energy. According to the pushover curve, the energy absorption of the structure is directly proportional to the base shear, maximum roof displacement, and elastic stiffness.

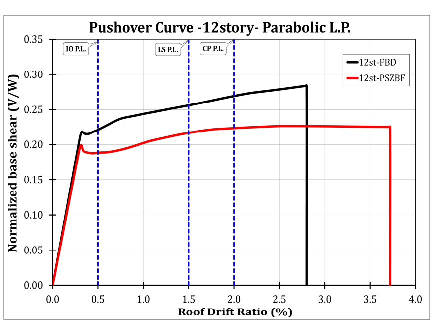
3. Results and Discussions

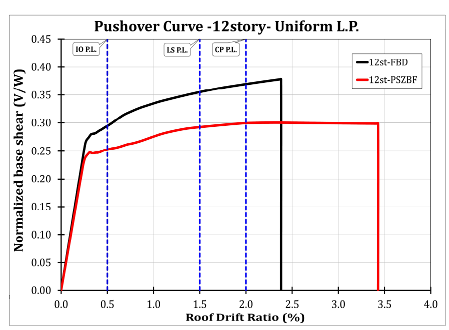
According to the results of pushover analysis, the energy absorption of the models and the increasing percentage in PSZBF models compared to the FBD models are shown in Table 2. The increasing percentage of the PSZBF models compared to the FBD models for the 12- and 16-story frames is about 43-50% and 17-23%, respectively. Although PSZBF models have lower maximum lateral resistance, they are able to absorb input energy by increasing the collapse lateral displacement. Also, by increasing the number of stories from 12 to 16, the energy absorption of PSZBF models is reduced by about 50% (figure 4 and 5).

Table 2. The Energy Absorption of the Models

Parabolic			Uniform		
Models	Energy Absorption (MJ)	Increasing Percentage*	Models	Energy Absorption (MJ)	Increasing Percentage
12st-FDB	1110	14.5	12st-FDB	1255	24.4
12st-PSZBF	12.71		12st-PSZBF	1561	
16st-FDB	1821	24.1	16st-FDB	1679	25.4
16st-PSZBF	2260		16st-PSZBF	2105	

*Increasing of PSZBF models to FBD models





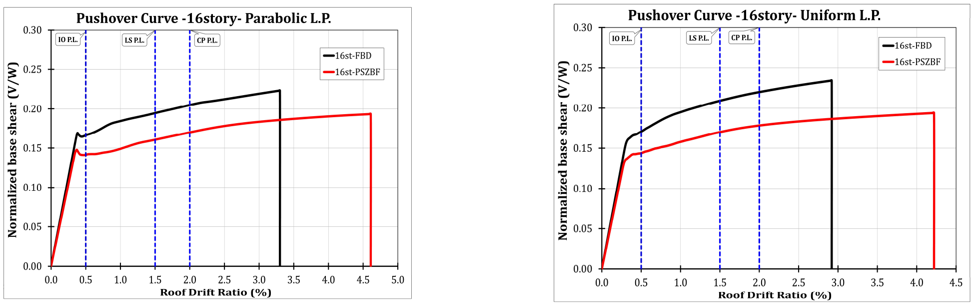


Figure 3. Pushover Curves of Models under Uniform and Parabolic Load Patterns

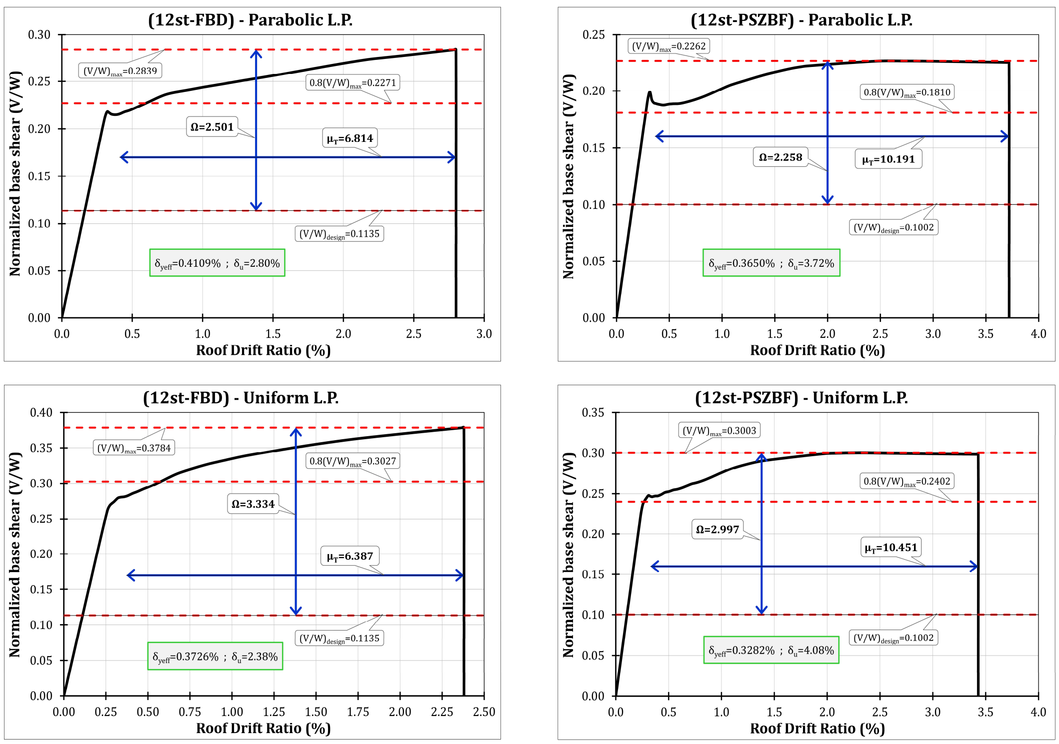


Figure 4. Seismic Performance Parameters of 12-Story Models

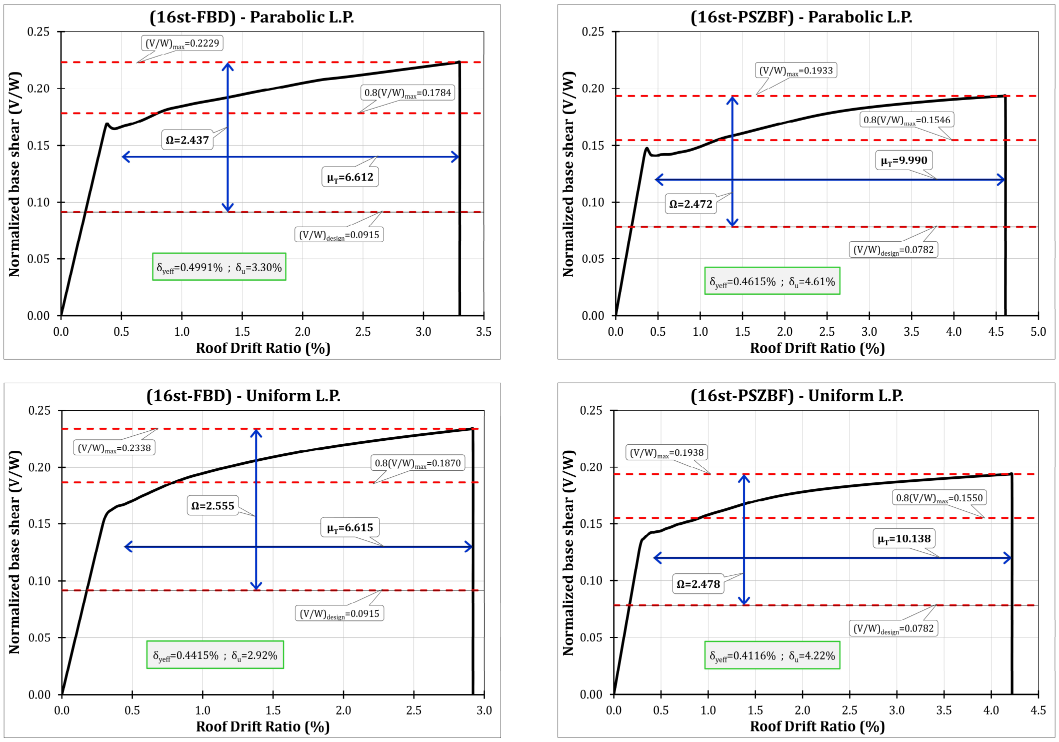


Figure 5. Seismic Performance Parameters of 16-Story Models

3. Conclusions

In order to compare the structural performance of the SZBF equipped with proposed hybrid damper designed by the PBPD method with the conventional SZBF, two high-rise 12- and 16-story SZBFs were designed according to these two cases. A comparative study of the models with nonlinear static analysis clearly shows the following results:

(1) Using the PBPD design method instead of the FBD method reduces the steel consumption by approximately 5.5-7.3% in the SZBF, which is expected to decrease further with the increasing number of stories.

(2) Since the PBPD method results in a weaker design of columns and braces than the FBD method by about 5-10%, the elastic stiffness of the PSZBF models is about 5% lower than the FBD models, that the elastic stiffness in both models can be assumed to be equal.

(3) Although PSZBF models have lower maximum lateral resistance than FBD models, they are able to absorb energy about 25% more in addition to increasing collapse lateral displacement.

4. References

[1] CEN - EN 1998-1, Eurocode 8, Design Provisions for Earthquake Resistance of Structures, "Part 1: General Rules, Seismic Actions and Rules for Buildings", European Committee for Standardization, Brussels, 2007.

[2] AISC-LRFD, American Institute of Steel Construction, "Load and Resistance Factor Design Specification for Structural Steel Buildings", Chicago, USA, 2016.

[3] Rajeev, P., Wijesundara, K.K., "Energy-based damage index for concentrically braced steel structure using continuous wavelet transform", Journal of Constructional Steel Research, 103:241-250, 2014.

[4] D'Aniello, M., Costanzo, S., Landolfo, R., "The influence of beam stiffness on seismic response of chevron concentric bracings", Journal of Constructional Steel Research, 112:305-324, 2015.

[5] Rai, D.C., Goel, S.C., "Seismic evaluation and upgrading of chevron braced frames", Journal of Constructional Steel Research, 59: 971-994, 2003.

[6] Khatib, I., Mahim, S., Pister, K, "Seismic behavior of concentrically braced steel frames", Earthquake Engineering Research Center, University of California, Berkeley, 1988.

[7] Leon R.T., Yang C.S., "Special Inverted-V-braced Frames with Suspended Zipper Struts". International Workshop on Steel and Concrete Composite Construction", National Center for Research on Earthquake, Taipei, Taiwan, 2003.

[8] Yang, C.S., Leon, R.T., DesRoches, R., "Pushover Response of a Braced Frame with Suspended Zipper Struts", Journal of Structural Engineering, 134: 1619-1626, 2008.

[9] Ozcelik, Y., Saritas, A., Clayton, P.M., "Comparison of Chevron and Suspended-Zipper Braced Steel Frames", Journal of Constructional Steel Research, 119: 169-175, 2016.

[10] Rossi, P.P., Quaceci, G., "A Design Procedure for Suspended Zipper-Braced Frames in the Framework of Eurocode 8", Journal of Earthquake Engineering & Structural Dynamics, 2017.

[11] Wijesundara, K.K., Nascimbene, R., Rassati, G.A., "Evaluation of the Seismic Performance of Suspended Zipper Column Concentrically Braced Steel Frames", Journal of Constructional Steel Research, 150:452-461-2018.

[12] McCormick, J., Aburano, H., Ikenaga, M., Nakashima, M., "Permissible Residual Deformation Levels for Building Structures Considering both Safety and Human Elements', Proceedings of the 14th world conference on earthquake engineering, Beijing, China, 2008, Paper No. 05-06-0071.

[13] ASCE 7-16, American Society of Civil Engineers, "Minimum Design Loads for Buildings and Other Structures", Reston, Virginia, USA, 2016.

[14] ANSI/AISC 360-10, American Institute of Steel Construction, "Specification for Structural Steel Buildings", Chicago, USA, 2010.

[15] IBC, International building code, International Code Council, INC. 2006.

[16] Jani, J.M., Leary, M., Subic, A., Gibson, M.A., "A review of shape memory alloy research, applications and opportunities", Journal of Materials and Design, 56: 1078-1113, 2014.

[17] FEMA-P695, "Quantification of building seismic performance factors", Applied Technology Council for FEMA, Redwood City, California, USA, 2009.

[18] ASCE/SEI 41-06, American Society of Civil Engineers, Structural Engineering Institute, "Seismic Rehabilitation of Existing Buildings", Reston, Virginia, USA, 2006.