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Simplified Design Method for the Performance-Based Seismic Design of Shear-Controlling Rocking-Isolation Podium Systems for Tall Buildings

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ABSTRACT

Reinforced concrete shear wall structures are the most commonly used lateral load resisting system for tall buildings. One of the critical design challenges for these structures using current prescriptive code-based design methods is to properly account for the contribution of higher modes of vibration to the overall dynamic response. It has been widely acknowledged that the actual seismic demands in these systems can be larger than predicted when using simplified design equations. These higher-mode effects are primarily attributed to the amplified dynamic response at higher frequency modes that are not controlled by the designated plastic-hinging mechanism at the base. This amplified dynamic response can cause unexpectedly higher structural and non-structural damage, making these structures more susceptible to service disruptions and extensive repairs following a major earthquake. To address this, base dual-mechanism systems that limit both shear force and overturning moment demands are being developed as a new class of seismic force-resisting systems to enhance the control of seismic demands and associated higher mode effects. Despite an increasing number of numerical studies that have demonstrated enhanced seismic resilience using these proposed base dual-mechanism systems, there is limited design methodology available to guide the preliminary design of these systems. This paper presents a simplified design method for the performance-based seismic design of these base dual-mechanism systems and the structures above, developed based on a previously proposed self-centering base dual-mechanism system termed the Shear-Controlling Rocking-Isolation Podium (SCRIP) system. The design methodology discussed in this paper is used to design four example core-wall tall buildings with heights of 45, 90, 150, and 300 meters, respectively, which are then analyzed using advanced nonlinear modeling and analysis techniques to demonstrate the adequacy of the proposed methodology. The analysis results were in reasonable agreement with the targeted response of the SCRIP system defined in the proposed PBSD procedure and confirmed that the buildings designed with the SCRIP system achieved overall seismic performances that exceeded the performance objectives set in the designs.

Keywords: higher-mode effects, tall buildings, rocking, self-centering, performance-based design

INTRODUCTION

The seismic performance of critical infrastructure and tall buildings has become a major design consideration for the sustainable and resilient development of urban centers in earthquake-prone regions. While conventional code-compliant structures are designed to meet the life safety requirement usually with significant damage under design-level earthquakes, recent advances in the Performance-Based Seismic Design (PBSD) methodologies provide the designers the means to design a structure with specific seismic performance targets (that typically exceed the code-prescribed requirements) and support the use of innovative designs to achieve set targets. This is especially useful for the design of critical infrastructure and tall buildings that are usually more complex in their seismic design, and have a more significant impact to the local community if damaged during earthquakes. Tall and slender buildings, in particular, are highly sensitive to dynamic loads linked to their higher-frequency vibration modes, which generally produce a more complex seismic response than lower-rise structures that are responding primarily in their fundamental modes. The influence of higher modes of vibrations (i.e., higher-mode effects) is especially significant for tall buildings that rely mainly on a base-yielding mechanism to limit the seismic demands along the height of the structure, such as ductile reinforced concrete shear wall structures that are commonly used in tall building construction, which poses significant design challenges for the proper seismic design of these type of structures. Recognizing the design challenges associated with higher-mode effects, a considerable amount of research has been conducted on accounting for higher-mode effects in the design process since the 1940s, which are summarized by Rutenberg [1] and more recently by Christopoulos and Zhong [2]. Alternatively, several higher-mode mitigation systems have been proposed that aim at limiting the seismic loads induced by higher-mode effects, which include multiple inelastic mechanisms along the height [3-5], as well as base-mechanism systems that limit both the shear and flexural demands [6-11]. While numerical analyses have been conducted alongside the proposal of each of these systems to validate their intended performance and ability to mitigate higher-mode effects, no method has yet been proposed to explicitly account for the higher-mode-limiting effect in a manner that can be easily implemented in a design process.

To this end, this paper proposes a simplified design method for the preliminary design of tall buildings incorporating one of the previously proposed base-mechanism systems for higher-mode effect mitigation, the Shear-Controlling Rocking-Isolation Podium (SCRIP) system, proposed by the authors to enhance the seismic resilience of tall buildings [11,12]. The proposed simplified design method consists of two main components, which are (1) designing the dual-base mechanism system using a set of design charts, and (2) protecting the rest of the structure for the maximum expected seismic force demands computed using closed-form equations. This method is developed as a preliminary design approach to determine the design resistance level of the SCRIP system, as well as the force envelopes used for the capacity design of the superstructure without any structural modeling or analysis. The proposed simplified design method is validated using Non-Linear Response History Analysis (NLRHA) for four example core-wall tall buildings with heights of 45, 90, 150, and 300 meters, analyzed using detailed 3-Dimensioanl (3D) Finite Element (FE) analyses. The mean base-mechanism responses as well as the superstructure force envelopes from the FE analyses are then compared with the estimates from the proposed method to evaluate their accuracy for tall buildings of various heights and fundamental periods.

FUNDAMENTAL MECHANICS OF THE SCIRP SYSTEM

The SCRIP system, as shown in Figure 1, is a dual base-mechanism system developed to control both the shear force and Overturning Moment (OTM) demands at the base of a tall building while ensuring full recentering capabilities in both horizontal directions [11,12]. This dual base-mechanism system incorporates a rocking podium designed to displace laterally (through the elastic rocking response of rocking columns) during the seismic response and recenter the structure after the earthquake, and energy-dissipating devices designed to yield and dissipate energy as the rocking podium moves. On top of the rocking podium is a rocking core wall designed to uplift slightly to control the base-moment demands and recenter the superstructure while uncoupling the flexural response of the superstructure from the lateral response of the rocking podium. The higher-mode mitigating capability and self-centering characteristics of the SCRIP system have been validated through numerical case studies of a benchmark tall building [11] and shaking table tests of a scaled specimen [13-16], demonstrating enhanced seismic resilience of structures equipped with the proposed system.

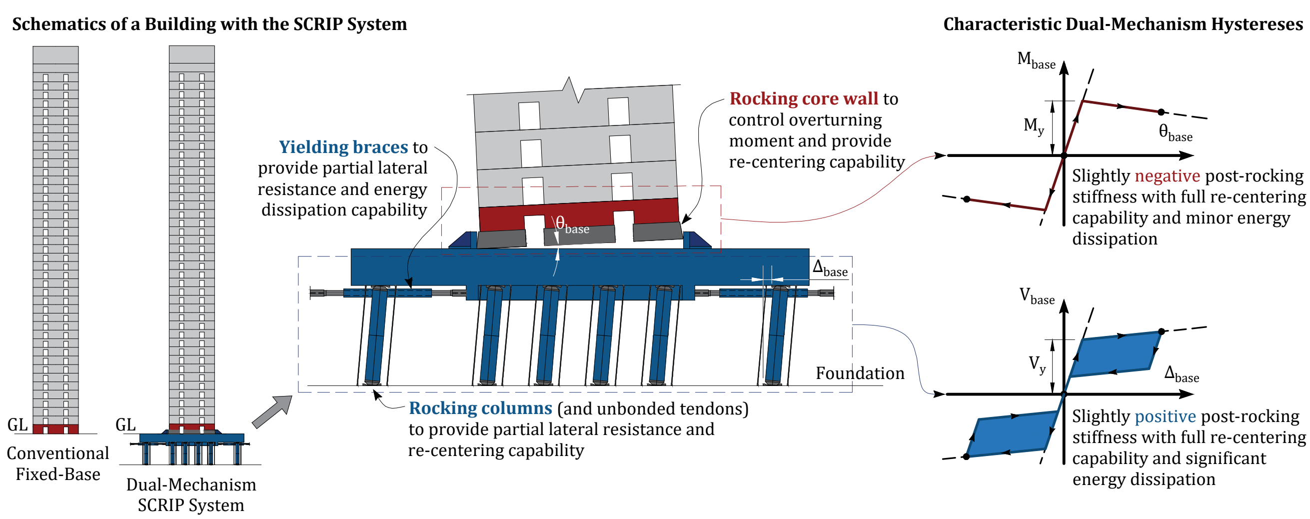

Figure 1. Fundamental Mechanics of the SCRIP System.

SIMPLIFIED DESIGN METHOD

Figure 2 presents an overview of the proposed design framework for the preliminary design of tall buildings with the SCRIP system [12,17]. This paper focuses on the two main components within this proposed design framework that are specifically developed to enable the quick establishment of a preliminary design of a tall building with the SCRIP system at its base, which can be used to develop a numerical model for detailed performance evaluation and detailed design. The first main component is the preliminary design of the target resistance levels of the dual-base mechanism system (i.e., the SCRIP system) using a set of design charts developed based on an extensive parametric study [15]. The second main component is the estimation of maximum expected seismic force envelopes along the height of the structure using closed-form equations that account for both higher-mode effects and the force reduction because of the dual-base mechanism system at the base.

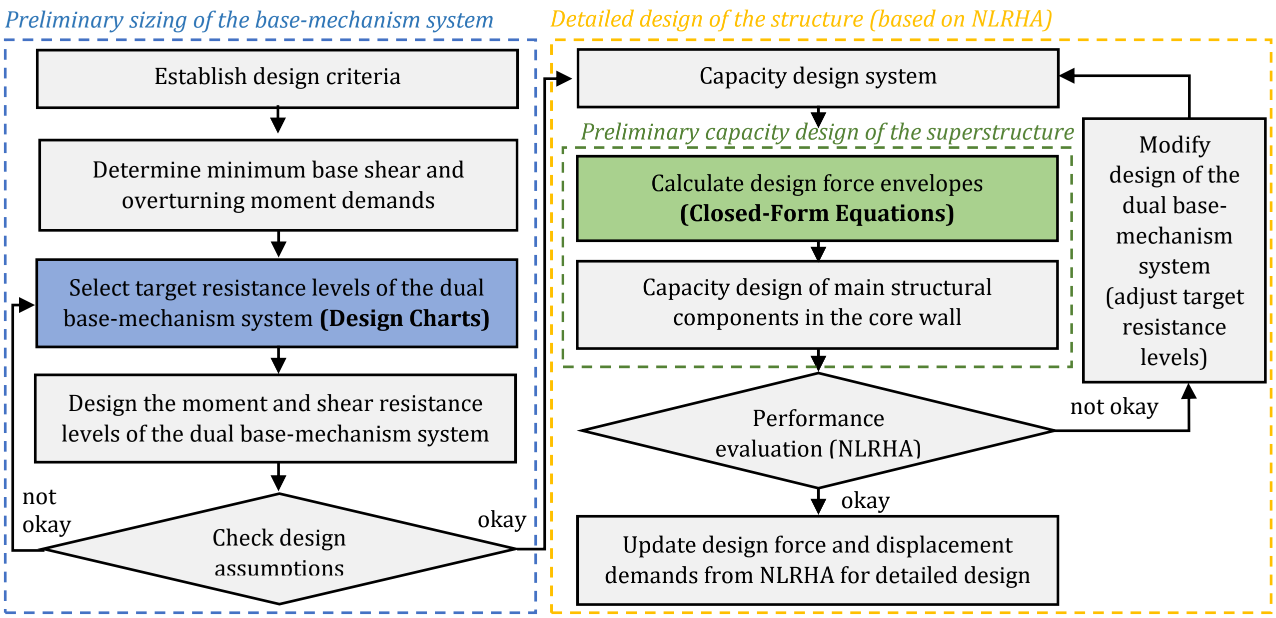

Figure 2. Overview of the Design Process.

Preliminary Design of the SCRIP System

Prior to selecting the target resistance levels of the SCRIP system, the minimum base shear and overturning moment demands should be determined, following requirements of established code provisions (e.g., [18]) as well as recommendations by the two main guidelines for the PBSD of tall buildings [19,20]. The SCRIP system should be sized such that its shear and overturning moment resistances are higher than the demands corresponding to the fixed-based wind and Service-Level Earthquake (SLE) events defined in the code provisions (e.g., [18]), thus emulating a fixed-based, no-rocking base condition of the structure under these loading scenarios. Based on the minimum resistance levels of the SCRIP system determined (hereafter denoted as $M_{rock,min}$ and $V_{SCRIP,min}$), the designer can proceed with the design by selecting the target resistance levels of the SCRIP system using the design charts presented in Figure 3, to set the baseline design of the SCRIP system with estimated base rotation demands θ_M and base lateral displacement demands Δ_V that can be accommodated by the overall design. Each subplot of Figure 3 represents generalized structures with SCRIP systems at their base that are designed with resistance levels as multiples of their minimum resistances, $M_{rock,min}$ and $V_{SCRIP,min}$, where the corresponding multipliers are denoted as η_M and η_V, for the base moment resistance level and shear resistance levels, respectively. The estimated base rotation demands θ_M is plotted in red-dotted lines and the estimated base lateral displacement demands Δ_V in blue-dotted lines, for a given fundamental period T_1 of a superstructure. It is worth noting that these design charts were developed with an intention to enable a fast and simplified preliminary sizing of the SCRIP system. More accurate values of the base rotation and displacement demands, considering site design spectra and specific building characteristics, should be obtained and verified based on the NLRHAs of the 3D numerical model in the detailed design stage. Details on how to size each component of the SCIRP system to achieve the target resistance levels are discussed in [17].

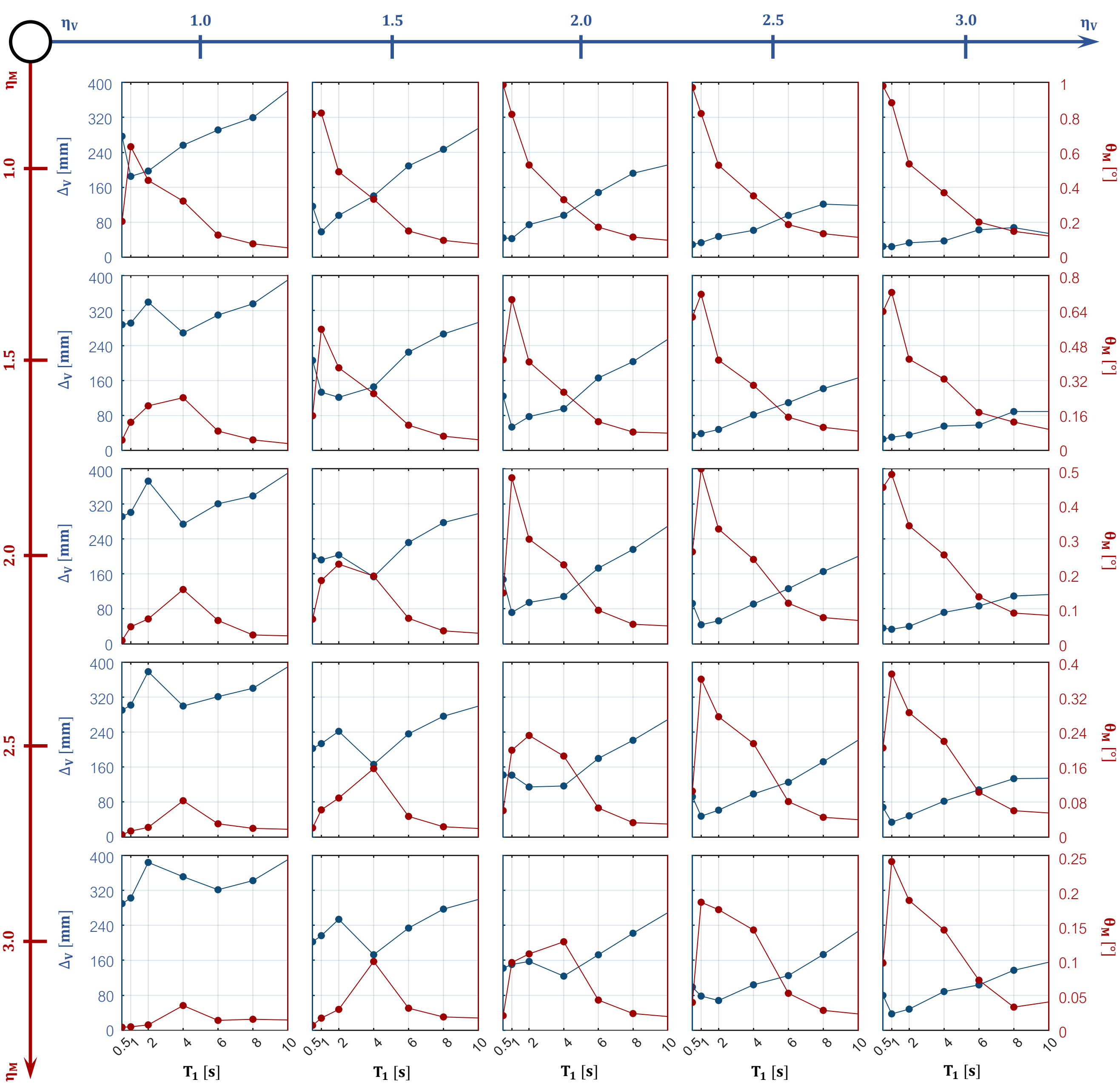

Figure 3. Design Charts for the Preliminary Design of the SCRIP System.

Preliminary Design of the Superstructure

This section discusses the estimation of seismic force demand envelopes along the height of the superstructure above the SCRIP using a set of closed-form equations. These equations are developed to estimate the force demands based on the superstructure's predominant periods in the first three modes, and the selected resistance levels of the SCRIP system. For the initial estimation, the second-mode period, T_2, and third-mode period, T_3, in each principal horizontal direction of the superstructure can be approximated based on the superstructure's fundamental period, T_1, as $T_2 = T_1/6.27$ and $T_3 = T_1/17.55$ [21,22]. These period estimates can be checked and updated later by performing modal analyses using the preliminarily designed structure. Because the SCRIP system is developed to mitigate higher-mode effects, three modes in each horizontal direction are found to be sufficient for the analysis of structures with the SCRIP system [12].

The closed-form equations presented in this section are extended based on the theoretical modal properties of a cantilever flexural beam with variable base shear and flexural restraints [13,23]. This method simplifies a typical tall building as a flexural cantilever beam with uniformly distributed mass and stiffness over its height, and uses a rotation and translational springs at the base to represent the dual-base mechanisms system (e.g., the SCRIP system). These assumptions enabled the derivation of the proposed closed-form equations for a quick estimation of seismic force demand envelopes considering the force-limiting effects of the dual-base mechanism system and the reduced higher-mode effects along the height of a tall building without the need for more complex analyses. The proposed closed-form equations are as follows:

$$V_{1,max}(z) = 1.5(M_{rock}/H)[1-(z/H)^2] \tag{1}$$

$$V_{2,max}(z) = \frac{W_{trib}\mathrm{S}_a(\mathrm{T}_n)}{39200}\left|16.4\sinh\frac{3.92z}{H} - 163\cosh\frac{3.92z}{H} + 16.3\sin\frac{3.92z}{H} - 5250\cos\frac{3.92z}{H}\right| \tag{2}$$

$$V_{3,max}(z) = \frac{W_{trib}\mathrm{S}_a(\mathrm{T}_n)}{70500}\left|51\sinh\frac{7.05z}{H} - 47.5\cosh\frac{7.05z}{H} + 50.9\sin\frac{7.05z}{H} - 2860\cos\frac{7.05z}{H}\right| \tag{3}$$

$$M_{1,max}(z) = M_{rock}[1-1.5(z/H)+0.5(z/H)^3] \tag{4}$$

$$M_{2,max}(z) = \frac{W_{trib}\mathrm{S}_a(\mathrm{T}_n)H}{153700}\left|16.4\cosh\frac{3.92z}{H} - 163\sinh\frac{3.92z}{H} - 16.3\cos\frac{3.92z}{H} - 5250\sin\frac{3.92z}{H}\right| \tag{5}$$

$$M_{3,max}(z) = \frac{W_{trib}\mathrm{S}_a(\mathrm{T}_n)H}{497000}\left|51\cosh\frac{7.05z}{H} - 47.5\sinh\frac{7.05z}{H} - 50.9\cos\frac{7.05z}{H} - 2860\sin\frac{7.05z}{H}\right| \tag{6}$$

where $V_{i,max}(z)$ and $M_{i,max}(z)$ are the i-th mode peak story shear and overturning moment (OTM) at height z from the ground. M_{rock} and V_{SCRIP} are the designed resistance levels of the SCRIP system at the base. Eqns. (7) to (9) are used to combine the individual modal responses, under the assumption that, when the peak overall response is reached, the first-mode response is at its maximum and the higher-mode responses are superimposed on the first-mode response but are limited by the base shear-mechanism, so that the combined peak base shear, $V_{b,max}$, does not exceed the shear resistance level, V_{SCRIP}.

$$V_{max}(z) = V_{1,max}(z) + R_V\sqrt{(V_{2,max}(z))^2 + (V_{3,max}(z))^2} \tag{7}$$

$$M_{max}(z) = M_{1,max}(z) + R_V\sqrt{(M_{2,max}(z))^2 + (M_{3,max}(z))^2} \tag{8}$$

$$R_V = (V_{SCRIP} - 1.5M_{rock}/H)/\sqrt{(V_{2,max}(0))^2 + (V_{3,max}(0))^2} \tag{9}$$

where R_V is a factor that accounts for the reduced higher-mode effects through the base shear-mechanism.

EVALUATION OF THE PROPOSED SIMPLIFIED DESIGN METHOD

Preliminary Design of the Prototype Structures

This section evaluates the performance of the simplified design method discussed above by applying it to the preliminary design of four prototype structures with different height and fundamental periods located in a site in Los Angeles, California. The assumed typical elevation and floor plan of the prototype structures is presented in Figure 4(a). The design spectra used for the preliminary design and subsequent NLRHAs are shown in Figure 4(b) for the four prototype structures.

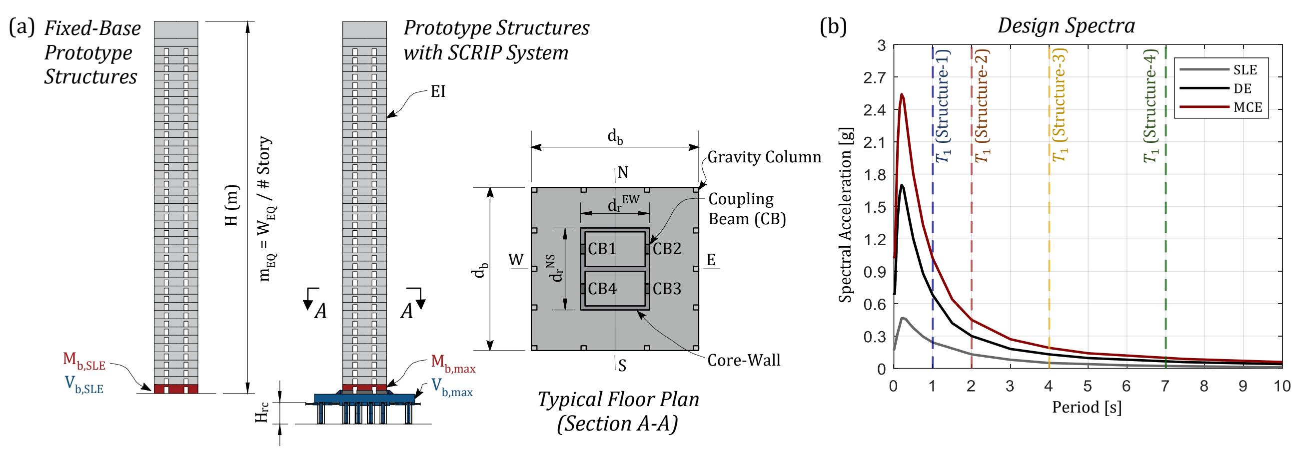

Figure 4. (a) Summary of Typical Floor Plans and (b)Design Spectra for the of Prototype Structures.

Table 1 summarizes the assumed key parameters of the prototype structures and the corresponding target resistance levels of the SCRIP system (i.e., η_V and η_M). The target resistance levels were selected considering the estimated base rotation demands $\theta_{b,exp}$ and base lateral displacement demands $\Delta_{b,exp}$ using the design charts in Figure 3, which will be compared with the predictions from the NLRHAs in subsequent sections. Based on the selected target resistance levels of the SCRIP system, the seismic force demand envelopes were estimated using the closed-form equations for each of the prototype structures. Figure 5 provides an overview of the prototype structures with their preliminary designed SCRIP systems and superstructures (i.e., the core walls). Detailed design of these prototype structures can be found in [12].

Table 1. Key Parameters of Example Design

Structure	H [m]	# Story	d_b [m]	W_{EQ} [MN]	W_{core} [MN]	Direction	d_r [m]	T_1 [s]	$V_{b,SLE}$ [MN]	$M_{b,SLE}$ [MNm]	η_V	η_M
Structure-1	45	15	15	50	34	NS	8.0	1.07	5.4	149.7	1.20	1.00
						EW	8.0	0.81	5.4	142.2	1.20	1.05
Structure-2	90	30	30	400	200	NS	15.0	2.06	25.0	1308.1	2.00	1.15
						EW	12.0	2.01	28.1	1202.2	1.80	1.00
Structure-3	150	50	40	700	405	NS	16.0	3.75	39.5	2124.8	2.03	1.41
						EW	12.8	4.10	42.7	2128.2	1.87	1.22
Structure-4	300	75	50	1800	880	NS	23.2	7.25	76.5	4261.4	1.96	1.88
						EW	20.0	7.01	80.0	4932.4	1.88	1.78

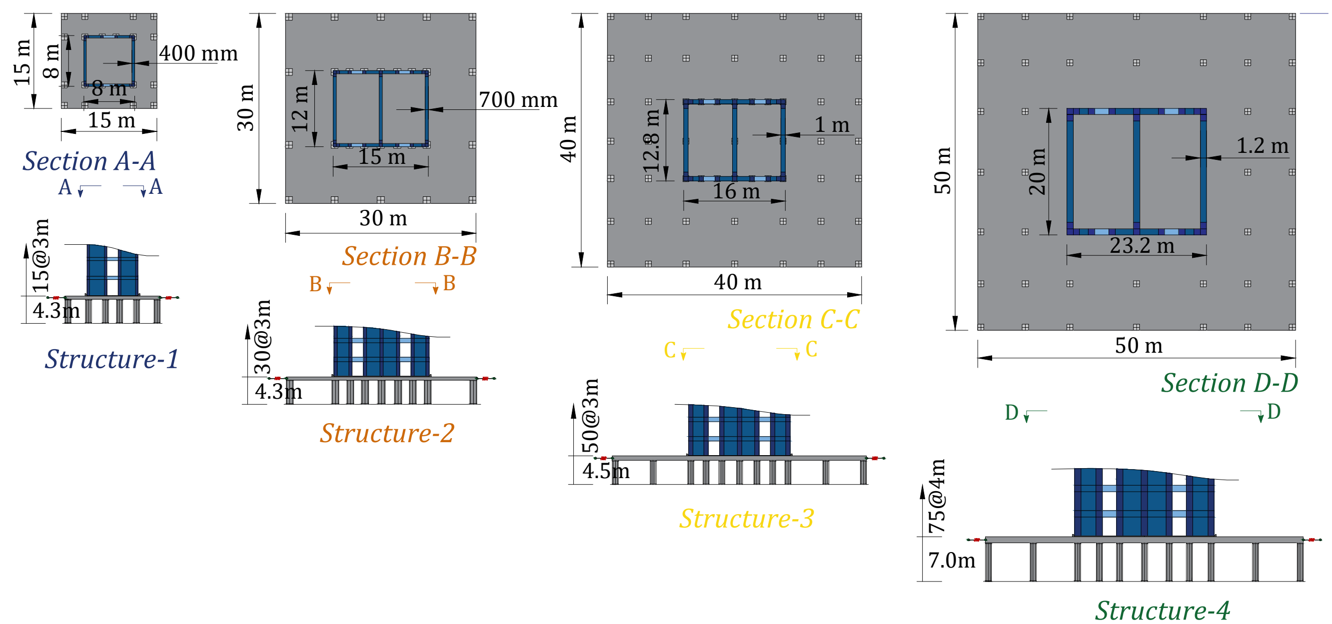

Figure 5. Overview of Prototype Structures.

Non-Linear Response History Analyses

With the preliminary design of the prototype structures, NLRHAs were then conducted following the recommendations specified in Chapter 16 of ASCE 7-22 [18] and the two main PBSD guidelines for tall buildings [19,20]. ABAQUS 6.13 [24] was used to construct detailed 3D FE models for the preliminarily designed structures. An overview of the modeling approach used for the modelling of the prototype structures is illustrated in Figure 6, whereas details are extended in [12]. Each prototype structure was then subjected to a suite of 20 tri-directional ground motions (i.e., two horizontal and one vertical) selected from the PEER NGA-West 2 Ground Motion Database [25] and scaled to the design spectra shown in Figure 4(b). In addition, each ground motion was extended with a free vibration period of 30 seconds to capture any residual deformations in the analysis.

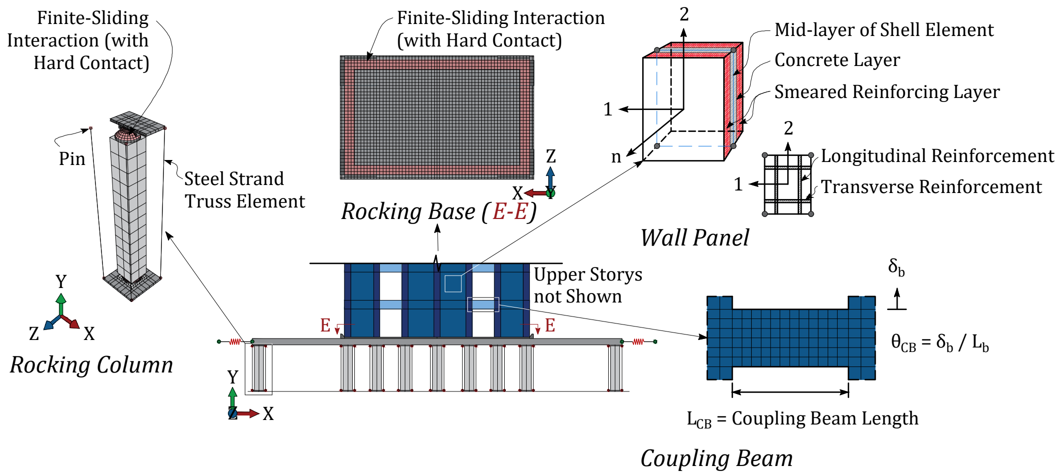

Figure 6. Overview of Modeling Approach.

Evaluation of the Simplified Design Method

To evaluate the performance of the simplified design method presented in this paper, the discussion on the NLRHA results in this section focus on the two main aspects of the simplified design method: (1) base rotation and displacement demands of the SCRIP system, and (2) seismic force demand envelopes along the height of the superstructure.

First, for the base rotation and displacement demands of the SCRIP system, Table 2 provides comparisons of these two parameters between the NLRHA results and those obtained from the design charts in Figure 3. As shown in Table 2, predictions using the design charts are generally slightly greater than the mean results from the NLRHA but bounded by the mean plus standard deviation of the 20 analyses for each prototype structure (except for the $\Delta_{lateral}$ of Structure-1, which has a prediction almost two times the mean NLRHA results). This suggested that the design charts provide conservative estimates of the base rotation and displacement demands, which would be appropriate for the purpose of preliminary design, especially considering the challenges in predicting the rotations and displacements of rigid rocking systems even with detailed numerical models [26,27].

As for the seismic force demand envelopes, Figure 7 compares the peak envelopes of story shear and OTM from the analyses and the closed-form equations. In general, demand envelopes estimated using closed-from equations were found to represent fairly well the average values obtained from the NLRHA for all four prototype structures. The results also suggested that the SCRIP system for all four prototype structures with different heights and fundamental periods were able to properly limit both the base shear and OTM demands as intended by their design. Results from individual analyses in most cases were bounded by the 1.3 amplified predictions – it is worth noting that the 1.3 amplification factor was recommended by ASCE 7-22 [18] for the capacity design of elements that are not explicitly controlled by a dedicated yielding mechanism, which is the case for concrete shear walls with base mechanisms. However, the SCRIP system's ability to mitigate higher-mode effects can also be clearly illustrated by comparing the estimated demand envelopes with and without the SCRIP system, plotted in Figure 7 as solid and dashed red lines, respectively. The differences in the solid and dashed red lines represent the amount of seismic force demands limited by the inelastic mechanism of the SCRIP system at the base.

Table 2. Comparison of Base Uplift and Lateral Displacement Demands from Analyses and Using Design Charts

	Δ_{uplift} (Moment Mechanism) [mm]		$\Delta_{lateral}$ (Shear Mechanism) [mm]	
	Mean (Standard Deviation)	Prediction	Mean (Standard Deviation)	Prediction
Structure-1	69 (50)	96	88 (35)	168
Structure-2	122 (78)	138	89 (39)	88
Structure-3	62 (31)	73	74 (50)	110
Structure-4	56 (29)	65	162 (78)	218

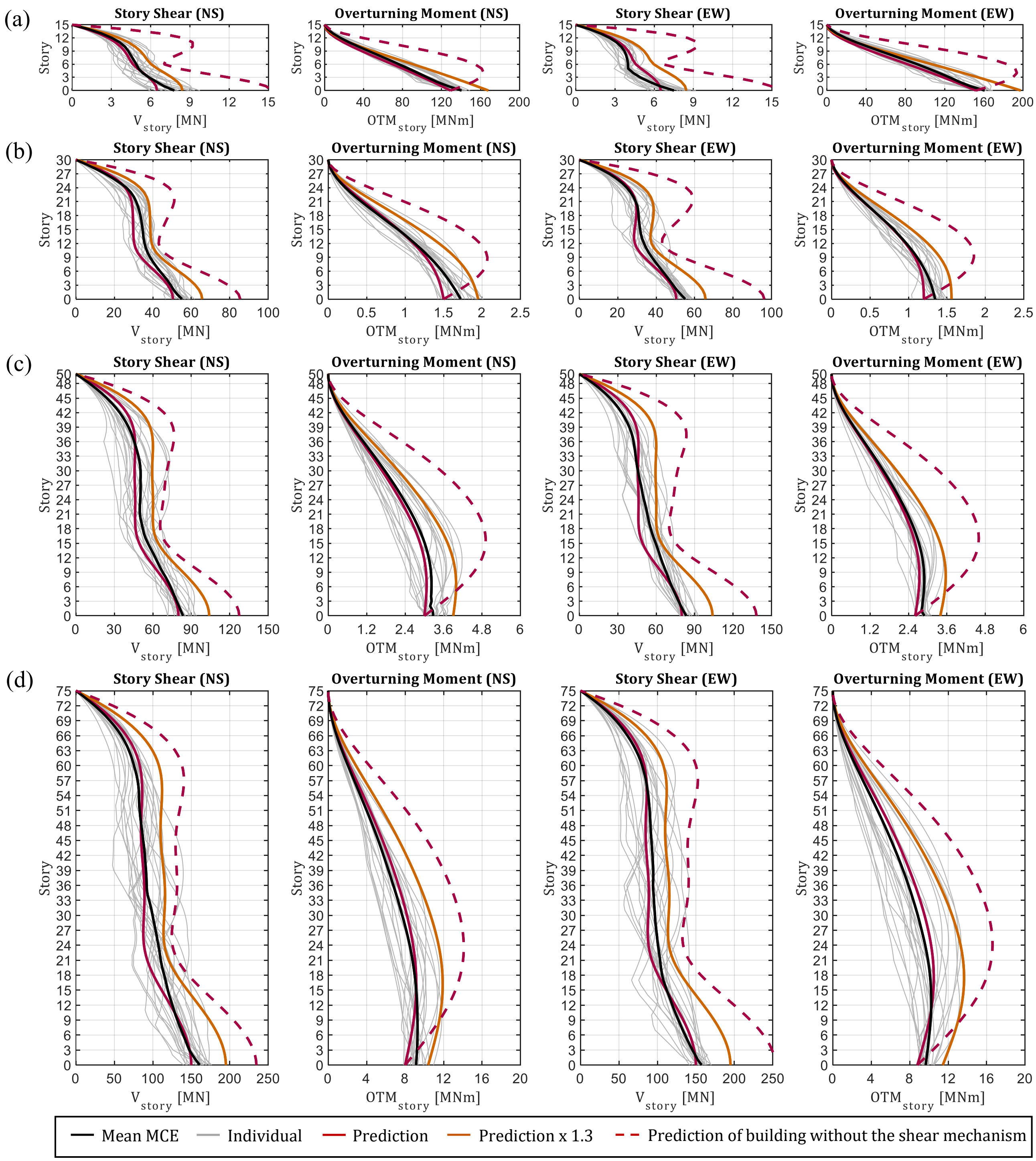

Figure 7. Comparison of Seismic Force Envelopes from Analyses and Using Design Equations.

CONCLUSIONS

Base dual-mechanism systems that limit both base shear and OTM demands have been proposed as a new family of seismic-resistant systems to mitigate higher-mode effects in tall buildings. To promote the practical implementation of such systems, this paper presented a simplified design method for the preliminary design of tall buildings utilizing such systems at their base to control higher-mode effects along the height that otherwise would have to be designed for. The proposed simplified design method comprised two main elements: one is to estimate the base rotation and displacement demands of the SCRIP system using a set of design charts, and the other is to estimate the seismic force demand envelopes along the height of the superstructure using closed-form equations. While the design of base dual-mechanism systems to date is typically based on a fully designed fixed-base benchmark building, this simplified design method can achieve a preliminary design without a reference structure or numerical model. The adequacy of the proposed simplified design method was demonstrated as part of this paper through the preliminary design and NLRHA of four prototype structures with various height and fundamental periods. Results of the NLRHA were found to be in reasonable agreement with the estimated displacement and force demands using the simplified design method for the SCRIP system.

The preliminary design and NLRHA presented in this paper focus on the SCRIP system and the lateral-resisting system of the superstructure (i.e., the core wall). It was assumed that the connections between the lateral-resisting system and the gravity systems are properly designed to transfer the required inertia forces, and that the SCRIP system details and connections are properly capacity-designed. In addition, both the design charts and the closed-form equations were developed assuming that the tall building has uniform mass and stiffness distribution along its height. Finally, it is worth mentioning that while this paper focuses on the SCRIP system, the design charts and closed-form equations were developed considering the general dual base-mechanism systems, therefore, this simplified design method, with further validation, has the potential to be applied to the preliminary design of tall buildings with other types of dual base-mechanism systems that control the overall seismic response of tall buildings by limiting the shear and OTM demands at their base.

ACKNOWLEDGMENTS

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