QUANTIFYING CRITICAL DESIGN PARAMETERS OF RC WALL-FRAME SYSTEMS FOR IMPROVED SEISMIC BEHAVIOUR

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Abstract

Lifeline buildings like hospital buildings are expected to remain operational after an earthquake event, to provide health care during mass casualties. But, hospital buildings and other important buildings like governance buildings also collapsed in many past earthquakes, rendering these buildings dysfunctional to attend the causalities and post-earthquake management of affected areas. Thus, design of such buildings requires special attention not usually required in design of normal buildings. Seismic design standards and documents recommend special guidelines with the intent of achieving the desired performance of these buildings during earthquakes. In particular, wall-frame structural systems are recommended by design documents (e.g., NDMA, 2016) for lifeline buildings like hospitals. Also, guidelines are provided on the minimum Structural Plan Density (SPD) and minimum Column-to-Beam Strength (CBSR) ratio required in the structural system.

The work presented in this paper investigates the effects of SPD and CBSR on seismic behaviour of RC wall-frame systems (suitable for lifeline structures) and compliments the current guidelines with additional quantitative recommendations. For the purpose, typical regular low-rise 4 storey buildings in high seismic zone (i.e., Seismic Zone V with Peak Ground Acceleration of 0.36g, as per IS1893:2016) with RC wall-frame structural systems are designed. Design and detailing are carried out to comply with the Indian Standards IS456:2000, IS1893:2016 and IS13920:2016. SPD values in each plan direction are varied (~1.6%, 3.3% and 5%) by varying the number of walls. Further, moment frames are designed for varying CBSR (2.0, 2.5, 3.0 and 3.5). The designed buildings are investigated of nonlinear behaviour by performing nonlinear static analysis in commercial software SAP2000. It is observed from the load-deformation behaviour that the lateral load capacity of buildings increases with increase in SPD and CBSR. Also, reasonably good progression of plastic hinges in ends of beams, along the height of the building is observed with increase in CBSR, in conjunction with reduction in plastic hinges in intermediate columns. SPD in the range of 3 to 5% is observed to be effective in improving the overall seismic behaviour of wall-frame systems. And, CBSR more than 3.5 is required to preclude formation of plastic hinges in columns. Parametric studies of buildings are also conducted, by varying SPD and CBSR in isolation, and nonlinear responses investigated; for e.g, CBSR required to achieve desirable nonlinear response for a given SPD, and vice versa. The study recommends RC wall-frame structural system to be adopted for improving lateral load resistance of lifeline buildings, and alongside provide minimum SPD and CBSR as proposed, to improve the functional use of these buildings post-earthquake.

Keywords: Wall-Frame systems; Lifeline Buildings; Structural Plan Density; Column-to-Beam Strength Ratio

1. Introduction

Hospital buildings are lifeline structures that must continue to remain operational by providing health care during mass casualties after an earthquake event. It is estimated that approximately 48 percent of hospital buildings are at risk for collapse or loss of function after potential future earthquake events [1]. Collapse of hospital buildings during past earthquakes jeopardizing structural and public safety are testimonies to the above. In particular, pre-code hospital buildings collapsed completely during the 1971 San Fernando Earthquake due to underestimation of seismic forces at the site of the hospital building [2]. Failures at beam-column joints due to minimal to non-existent confinement through the joint were primary reasons for failure of hospital building during 1985 Mexico City Earthquake [3]. Later, in 1995 Kobe earthquake, the Miyagi Hospital building suffered second floor collapse because of discontinuity in the structural walls above second floor [4]. Also, in 1994 Northridge, 2001 Bhuj and 2003 Bam earthquakes, significant structural damages due to formation of plastic hinges in columns leading to partial or complete collapse were observed in hospital buildings [5]. Even presence of structural walls with braced frames could not save the Victor Rios Ruiz Hospital building during the 2010 Chile Earthquake. These collapses or significant damages incurred in these buildings during past earthquakes resulted in dysfunctional emergency health care facilities. Hence, special attention must be given during design, to ensure the hospitals are structurally safe to prevent loss of life during earthquakes (*no collapse*), alongside ensuring post-earthquake functional use of the building (*occupiability*).

In view of maintaining the structural safety of hospital buildings during and after an earthquake, special guidelines recommended by seismic design standards and documents must be followed; design standards and documents have stipulated special guidelines for design of hospital buildings (under the category of *important buildings*). These guidelines are in general based on the local conditions like location, soil conditions etc., The Indian standard IS 1893 (1), 2016 [6], specifies an Importance factor I of 1.5 to be used for design of hospital buildings , in the estimation of seismic force imposed on the building. But, use of I does not guarantee the structural safety, along with meeting the required performance of *occupiability*. Also, there is no clarity on structural system and detailing schemes to be adopted to meet the performance [IS 1893 (1), 2016 [6]; IS13920, 2016 [7]].

Nevertheless, guidelines are available for seismic structural safety of hospital buildings [8, 9]. FEMA recommends that (i) 50% greater earthquake forces must be used for design of hospital buildings than for normal buildings, i.e., the importance factor of 1.5 must be used while calculating base shear, and (ii) the inter-storey inelastic storey drift must be limited to 1%. Some of the salient NDMA recommendations are: (i) prohibition for use of unreinforced masonry as structural system material (ii) adoption of *wall-frame structural system,* designed as per IS 13920: 2016 [7], (iii) provision of Column-to-Beam Strength Ratio (CBSR) of 2 at all joints of moment frame, (iv) arrangement of structural walls with at least 4% Structural Plan Density (SPD), and (v) prohibition of open ground storeys, soft and weak storeys. In addition, separate guidelines for safety of non-structural elements in a hospital building are available [8]. These guidelines are expected to help increase strength and stiffness of these buildings leading to less imposed deformation demand and thereby less damage during earthquake events. Buildings designed following these guidelines are expected to perform better during earthquakes; nevertheless, there is a need to quantity and confirm the guidelines.

While international seismic design documents do not provide special design recommendations for design of hospital buildings explicitly, recommendations on specific design requirements for design of special moment frames and wall-frame systems are provided. Tables 1&2 list some of these recommendations from various seismic design documents for design of special moment frames and wall-frame systems. The design parameters listed include Importance Factor I, Column-to-Beam Strength Ratio (CBSR), Structural Plan Density (SPD), Response Reduction Factor R, elastic/inelastic inter-storey drift limit and design earthquake.

Table 1: Seismic Design guidelines for Special Moment Frames

Standard/ Source	*Parameters*					*Storey Lateral Drift Limit*	
	I	*CBSR*	*SPD*	*Design Earthquake (Return Period in years)*	*Response Reduction Factor R*	*Elastic*	*Inelastic*
NDMA, 2016 [8]	-	-	-	-	-	-	-
IS 1893 (1), 2016 [6]	1.5	1.4	-	-	5	$0.004h_s$	-
NCh433, 1996 [10]	1.2	-	-	-	2	-	$0.002h_s$
NZS 1170.5: 2004 [11]	-	1.3	-	-	-	-	$0.025h_s$
ASCE 7- 10 [12]	1.5	-	-	475	8	-	$0.01h_s$
Euro Code 8, 2004 [13]	1.4	-	-	475	*q*	$0.005h_s$	-
ACI 381-14 [14]	-				-	-	-
OSHPD, 2008 [15]	-		-	-	8	-	$0.0133h_s$
McBean P, 2013 [16]	-	-	-	-	-	$0.005h_s$	-
FEMA 577, 2007 [9]	1.5	-	-	-	-	-	$0.01h_s$

Table 2: Seismic Design guidelines for Wall-frame System

Standard/ Source	*Parameters*					*Storey Lateral Drift Limit*	
	I	*CBSR*	*SPD*	*Design Earthquake (Return Period in years)*	*Response Reduction Factor R*	*Elastic*	*Inelastic*
NDMA, 2016 [8]	-	≥2	≥4	-	IS 1893	$0.004h_s$	-
IS 1893 (1), 2016 [6]	1.5	1.4	-	-	5	$0.004h_s$	-
NCh433, 1996 [10]	1.2	-	-	-	2	-	$0.002h_s$
NZS 1170.5: 2004 [11]	-	-	-	-	-	-	$0.025h_s$
ASCE 7- 10 [12]	1.5	-	-	475	7	-	$0.01h_s$
Euro Code 8, 2004 [13]	1.4	1.3	-	475	*q*	$0.005h_s$	-
ACI 381-14 [14]	-	1.2	-	-	-	-	-
OSHPD, 2008 [15]	-	1.2	-	-	8	-	$0.0133h_s$
McBean P, 2013 [16]	-	-	-	1500	-	$0.005h_s$	-
FEMA 577, 2007 [9]	1.5	-	-	-	-	-	$0.01h_s$

In the tables above, q is behaviour factor = $q_0 k_w$, q_0=5.4; $0.5 \leq k_W = (1+\alpha_0)/3 \leq 1$; α_0 aspect ratio of walls; h_s Height of the storey.

This paper presents investigations to confirm the adequacy of seismic design and detailing provisions pertaining to hospital safety stipulated in design standards and documents; NDMA guidelines are considered for the study. Numerical investigations and observations are presented of nonlinear static seismic behaviour of wall-frame systems, with varying SPD of structural walls and CBSR of moment frames. The study is limited to important, low-rise (4 storeys) RC wall-frame system buildings with regular frame grid (in plan). Soil-structure interaction is not included; buildings are considered to rest on hard strata. Beam-column joints are assumed to be infinitely stiff and strong, thereby assuming no damage in them. Shear failure is precluded by capacity design and members are designed to respond dominantly in flexural actions. Structural walls are expected to undergo damage in axial, flexural and shearing actions.

2. Numerical Study

A G+3 building with: plan size 20 m × 15 m, storey height 3m, and bay size 4m located in seismic zone V (Zone Factor of 0.36g); 230mm thick exterior (with 20% openings) and 150mm thick interior URM infill walls; columns fixed at base and founded on hard rock is considered. Live load of 3kN/m^2, and floor finish of 1kN/m^2 are considered, in addition to dead loads [6]]. Numerical modeling and linear elastic structural analysis and design are carried out in commercial software ETABS and nonlinear static analyses in SAP2000 [17]. Frame members are modeled using lineal elements and structural wall as *equivalent column* element. Design and detailing conforms to the Indian Standards [6, 8, 18]. For the same plan size, number of structural walls is varied to achieve different SPDs and the behaviour of the structure is studied (Table 3 and Figure 1). In total, one bare frame and 3 wall-frame system buildings are designed, detailed and their nonlinear static behaviour compared to draw inferences. The SPDs and fundamental period of buildings are listed in Table 3.

Table 3: Building Details

Building Type	SPD of walls in each principal plan direction (%)	Fundamental Period T (s)
Bare Frame	0	0.48
Wall-frame System 1	1.67	0.60
Wall-frame System 2	3.33	0.43
Wall-frame System 2	5.0	0.35

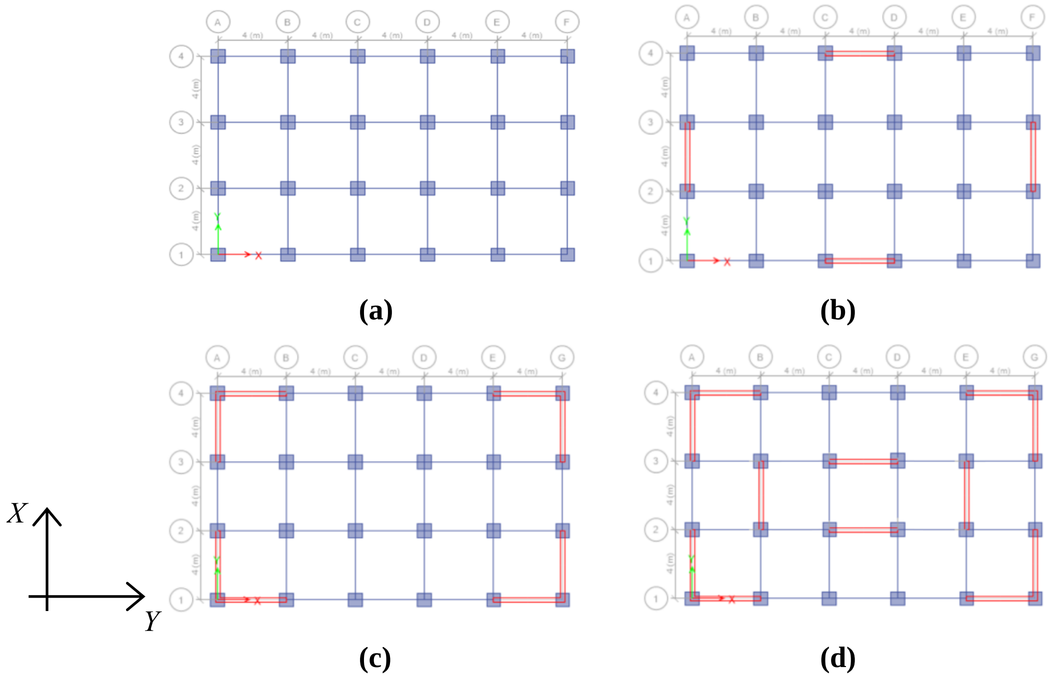


Fig. 1 – Structural grid of study buildings: (a) Bare Frame, (b) Wall-frame System 1, (c) Wall-frame System 2, and (d) Wall-frame System 3

Further, linear elastic structural analysis results from ETABS are used to design beams, columns and walls based on hand-calculations. Axial-flexure (*P-M*) interaction curves are developed for designed critical columns, and checked for conformance with axial stress ratio limitation and minimum CBSR stipulated in IS

13920 (2016). The check for axial stress is performed for all the load combinations considered. Design is iterated to comply with the checks. *P-M* interaction curve of a typical column which satisfies the checks above are shown in Figure 2 [19]. Similar design and checks are carried out for all building types. Design details of select members/structural element are listed in Table 4 and Table 5. As the SPD increases, the loads on frames start decreasing leading to decrease in bending moment and shear force demand in beams and columns. The values are less compared to that of bare frame, and hence the reinforcement required is lesser in frames in wall-frame systems.

Pushover analysis is performed of designed buildings in SAP2000. Inelasticity in frame members and structural walls is modeled using section designer option in SAP2000, based on the design details of beams and structural walls (Tables 4 & 5 show the members details for a CBSR of 3.5). Flexural hinges in beams, axial-flexure interacting hinges in columns, and both axial- flexure interacting hinges and shear hinges are defined in structural walls [20]. Flexural and axial-flexure interacting hinges are defined at a relative distance of 5 and 95 percent of length of beams and columns. Shear hinges in walls are defined at the centre. Axial flexure interacting hinges are defined at a relative distance of 5 and 95 percent of height of structural walls. Confinement effects of concrete are also considered, as per Mander's confinement model [21].

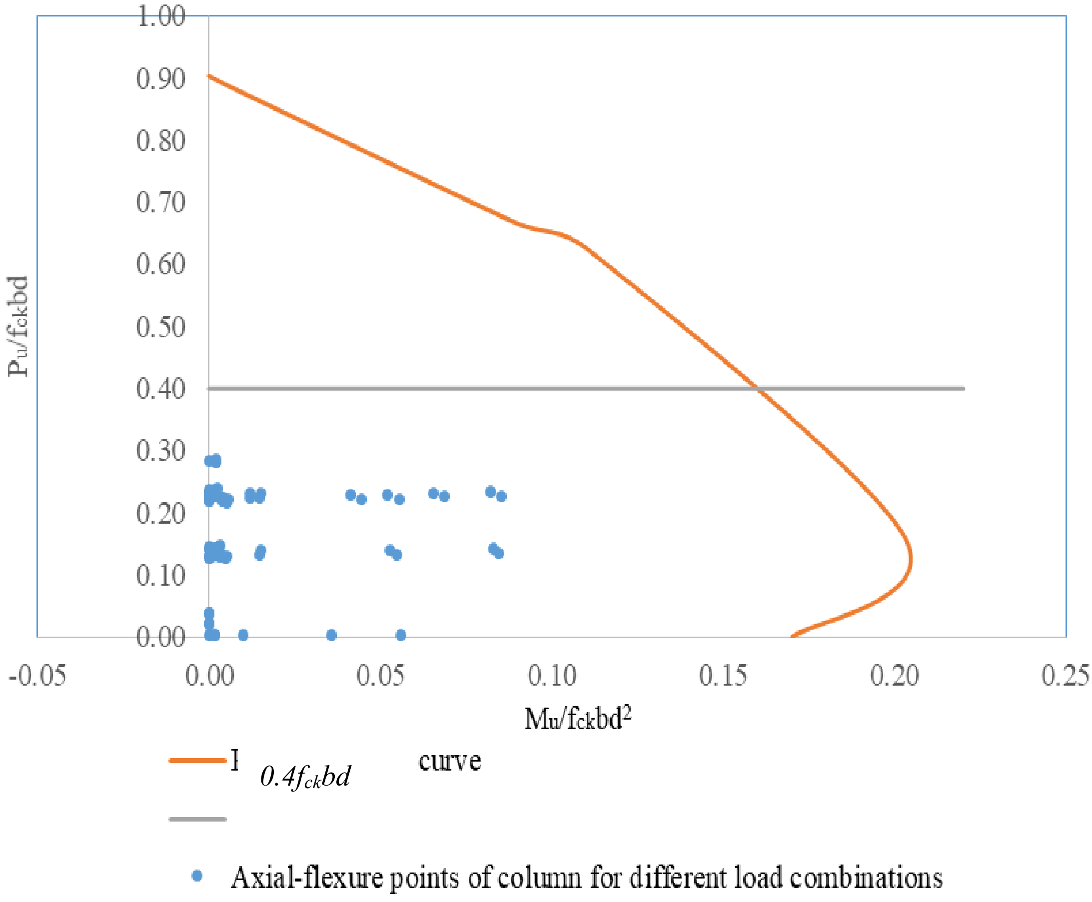


Fig. 2 – P-M Interaction curve of critical column at storey 2, in Wall-frame System 1

Table 4: Select Building Details I

Building Type	*Storey*	*SPD (%)*	*Reinforcement in wall*		*Beams*	*Columns*
			Vertical (mm^2)	*Horizontal* (mm^2)	*Dimensions (mm×mm)*	*Dimensions (mm×mm)*
Bare Frame	1	0	0	0	400x400	650x650
	2				400x400	650x650
	3				400x400	650x650
	4				400x400	650x650
Wall-frame System 1	1	1.67	3166	10852	400x400	700x700
	2				400x400	700x700
	3				400x400	700x700
	4				400x400	700x700
Wall-frame System 2	1	3.33	4296	12209	400x400	750x750
	2				400x400	750x750
	3				400x400	750x750
	4				400x400	750x750
Wall-frame System 3	1	5	4974	14244	400x400	700x700
	2				400x400	700x700
	3				400x400	700x700
	4				400x400	700x700

Table 5: Select Building Details II

Building Type	*Storey*	*Longitudinal tension reinforcement in beam* (mm^2)	*Longitudinal reinforcement in column* (mm^2)	*Minimum CBSR*	*Transverse Reinforcement*	
					Beam	*Column*
Bare Frame	1	3437	14779	3.5	Y10@100mm	Y8@100mm
	2	3927	14779	3.5	Y10@100mm	Y8@100mm
	3	2946	12868	3.5	Y10@100mm	Y8@100mm
	4	1964	12868	3.5	Y10@100mm	Y8@100mm
Wall-frame System 1	1	2455	19292	3.5	Y10@100mm	Y8@100mm
	2	2946	19292	3.5	Y10@100mm	Y8@100mm
	3	2455	16085	3.5	Y10@100mm	Y8@100mm
	4	1964	16085	3.5	Y10@100mm	Y8@100mm
Wall-frame System 2	1	2455	19312	3.5	Y10@100mm	Y8@100mm
	2	2946	19312	3.5	Y10@100mm	Y8@100mm
	3	2455	19312	3.5	Y10@100mm	Y8@100mm
	4	1964	19312	3.5	Y10@100mm	Y8@100mm
Wall-frame System 3	1	1964	14779	3.5	Y10@100mm	Y8@100mm
	2	1964	14779	3.5	Y10@100mm	Y8@100mm
	3	1964	14779	3.5	Y10@100mm	Y8@100mm
	4	1964	14779	3.5	Y10@100mm	Y8@100mm

3. Discussion of Results

Using pushover analyses results, graphs are drawn between seismic coefficient (ratio of base shear V and seismic weight W) and lateral drift (%). Progression of inelasticity and collapse mechanisms of buildings are observed. Pushover response curves and collapse mechanisms of study buildings (Figures 3-10) suggest:

(1) Lateral strength increases with increase in SPD of structural walls and CBSR in frame members;

(2) Lateral strength is maximum and drift capacity minimum in building with highest SPD;

(3) With CBSR of 2 (as per NDMA), the maximum lateral strength is attained in buildings with SPD 3.33% to 5%. Drift demand is minimum in these buildings (Fig. 3). This confirms *occupiability* performance of the structure;

(4) With increase in SPD, the force and displacement demand on building reduces. Building behaves nearly elastically during earthquake loading.

(5) With increase in CBSR, number of beams in inelastic state increases and number of columns in inelastic state reduces;

(6) CBSR of 3.5 with SPD 5% also is not able to completely prevent formation inelasticity in columns (Figure 10); higher CBSR is required to preclude column hinges.

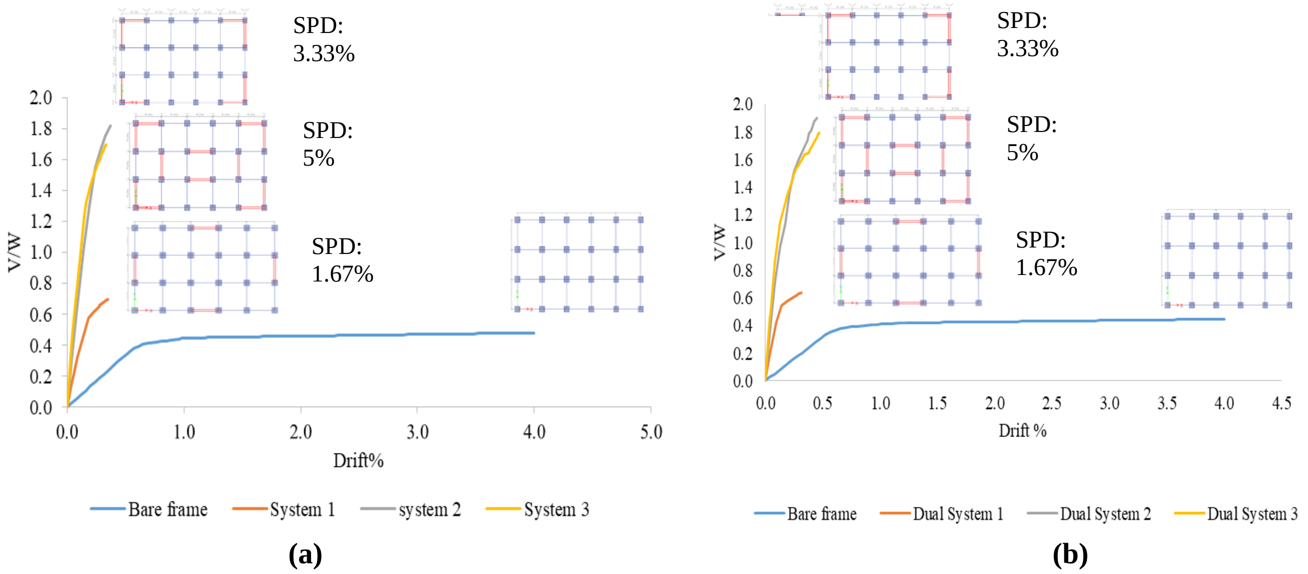


Fig. 3–Pushover curve of building designed with CBSR 2 in (a) x- direction; (b) y- direction

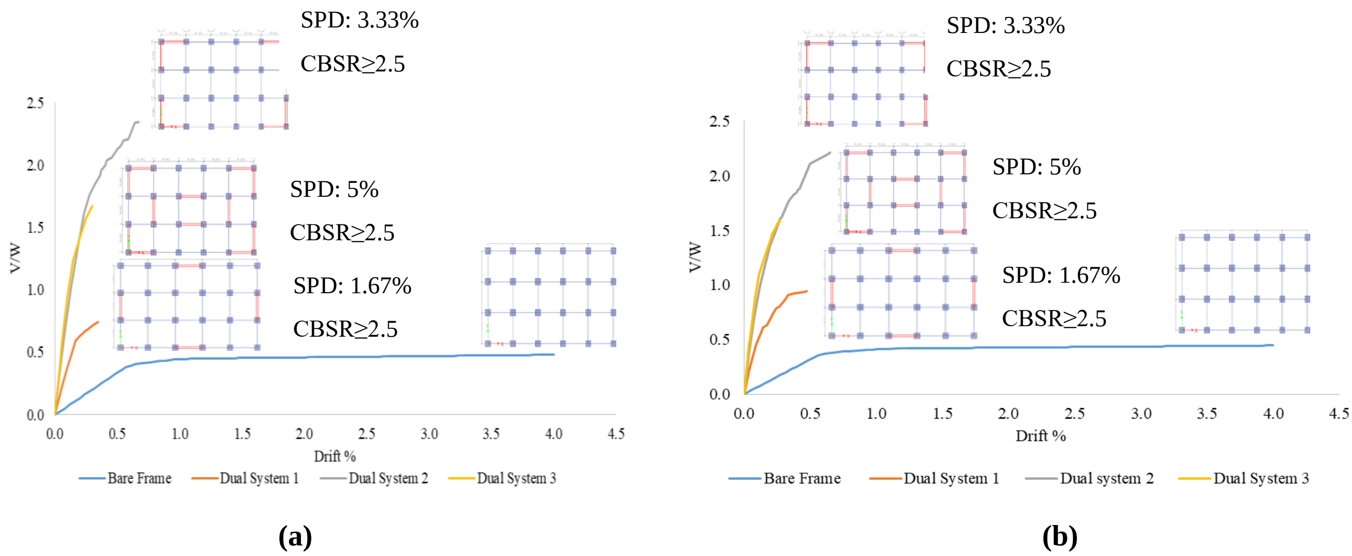
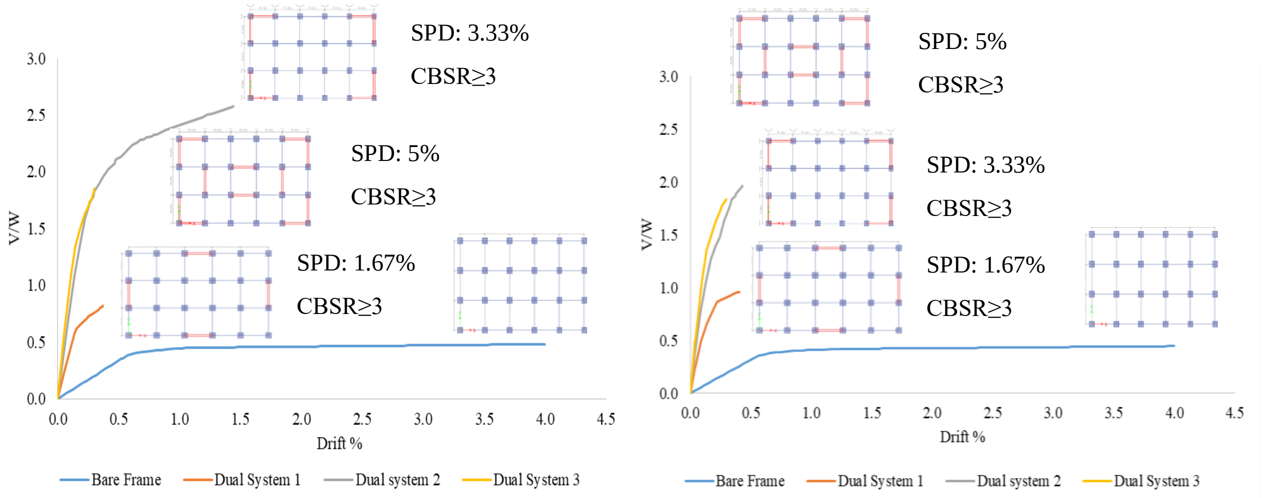
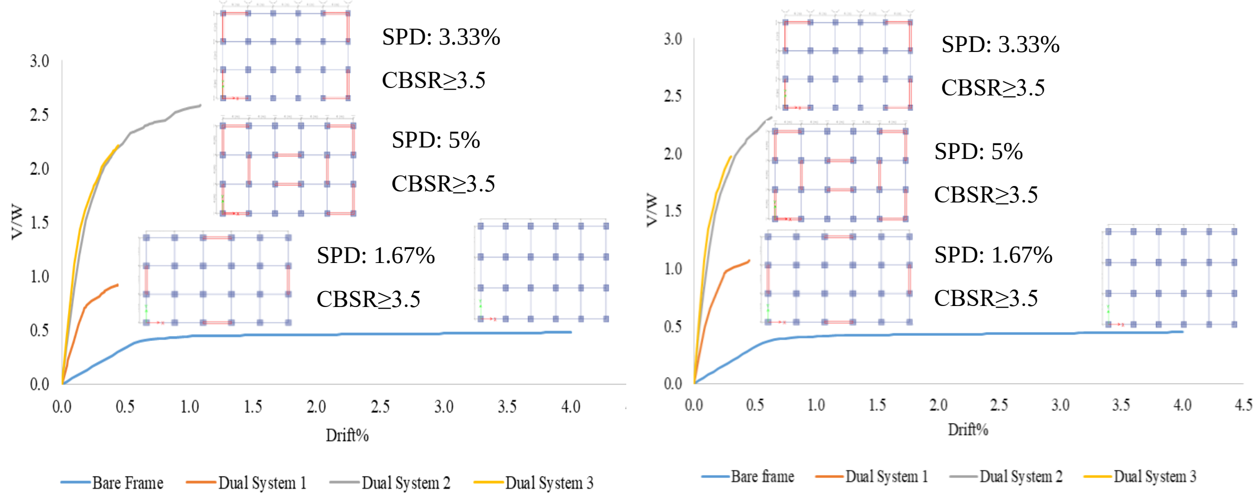


Fig. 4–Pushover curve of building designed with CBSR 2.5 in (a) x- direction; (b) y- direction



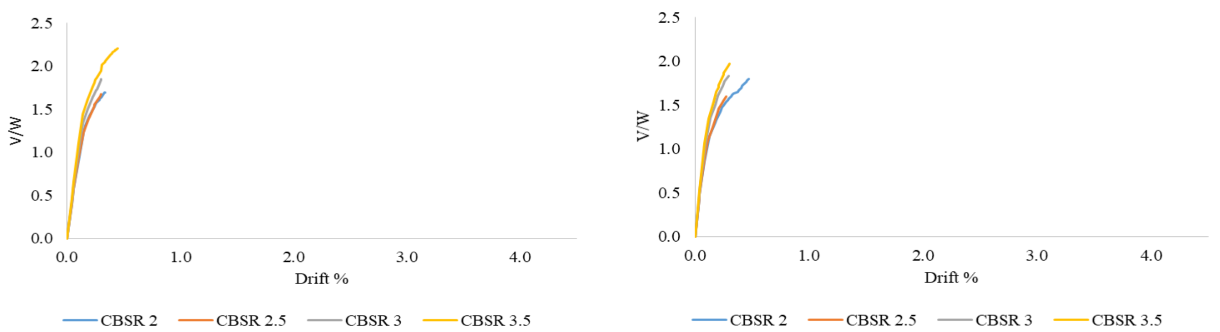
(a) **(b)**

Fig. 5–Pushover curve of building designed with CBSR 3 in (a) x- direction; (b) y- direction



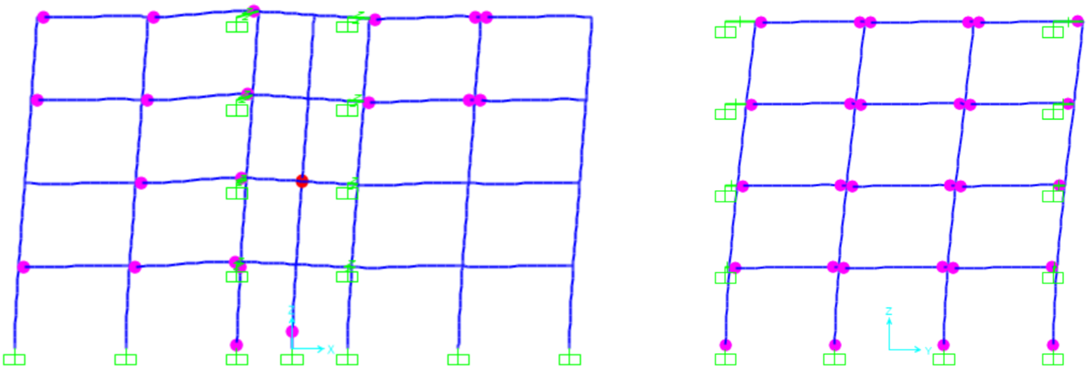
(a) **(b)**

Fig. 6–Pushover curve of building designed with CBSR 3.5 in (a) x- direction; (b) y- direction



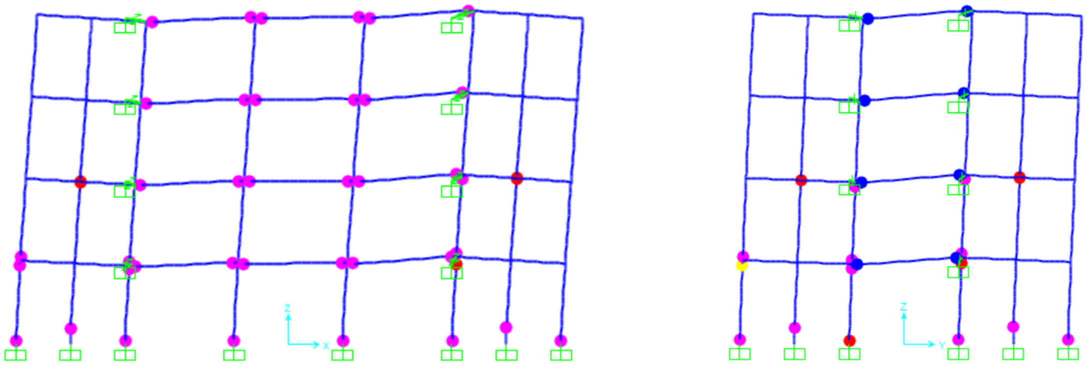
(a) **(b)**

Fig. 7–Pushover curve of building designed with CBSR 2, 2.5, 3, and 3.5 with SPD 5% in (a) x- direction; (b) y- direction



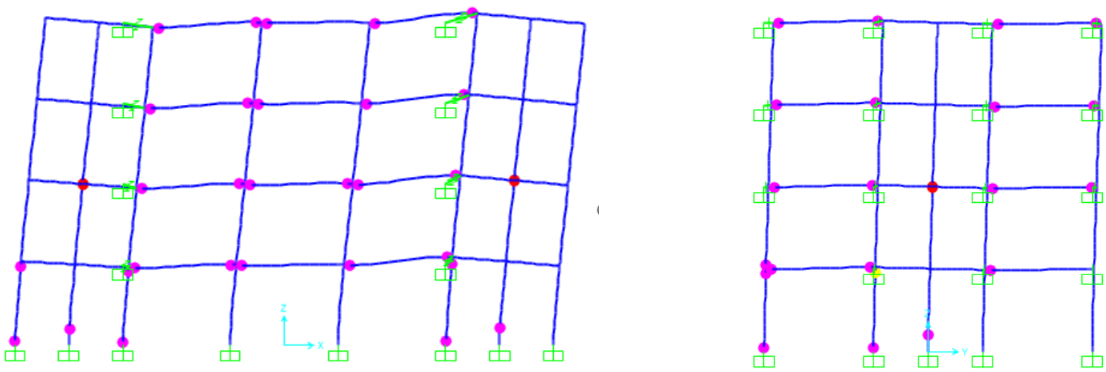
(a) **(b)**

Fig. 8– Inelasticity in wall-frame system 1, designed with CBSR 3.5: (a) x direction; (b) y direction



(a) **(b)**

Fig. 9– Inelasticity in wall-frame system 2, designed with CBSR 3.5: (a) x direction; (b) y direction



(a) **(b)**

Fig. 10– – Inelasticity in wall-frame system 3, designed with CBSR 3.5: (a) x direction; (b) y direction

4. Conclusions

The salient conclusions drawn from this study are:

(1) Stiffness of buildings increases with increase in SPD of structural walls, thereby significantly enhancing resistance to lateral loads.

(2) For typical buildings similar to that considered in this study, SPD in the range of 3 to 5 percent is effective to meet the intended performance requirement of post-earthquake occupiability. Such structures will have superior lateral strength and stiffness to remain functional even after the earthquake.

(3) CBSR of 2 is inadequate to preclude formation of column hinges in intermediate storeys. It is required to provide CBSR more than 3.5 to completely preclude hinges in intermediate columns.

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