Effect of Strong Column Weak Beam (SCWB) ratio on seismic vulnerability of 2-story RC frame and its fragility analysis.

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ABSTRACT: *This study conducts nonlinear static analysis to assess the risk of collapse of 2-storey special moment resisting RC frames designed using different Strong Column -Weak Beam. (SCWB) ratio of 1.2, 1.4,1.6 and 1.8. Four interior RC frames are designed using provisions of Indian Standards IS 456-2000, IS-1893:2016 and IS-13920:2016 for seismic zone IV and medium soil type. In order to assess the seismic fragility, HAZUS methodology is considered and fragility curves are generated as per four damage state suggested by Barbet et al. The results show that there is no major improvement in seismic performance of RC frames. The probability of collapse varies from 16% to 13% in case of 1.2 SCWB ratio to 1.8 SCWB ratio, respectively.*

Key Words: *Nonlinear static analysis, Strong Column-Weak Beam (SCWB) ratio, fragility analysis, probability of collapse.*

Introduction

During earthquake , columns are expected to be stronger than the beam in buildings . Further, the beam and column joint should be strong enough to transfer the inertia forces safely to the ground.. The method of designing RC buildings with beams to be ductile weak than columns is called the "Strong column weak beam" design method. This is achieved through capacity design of columns as per the latest revision of IS 13920:2016, which suggests a 1.4 SCWB ratio or greater.

$$\sum Mc \geq 1.4 \sum Mb$$

Where , For interior joint
$\sum Mb = M_{bs} + M_{bh}$ and $\sum Mc = Mc1+Mc2$
For exterior joint,
$\sum Mb = M_{bh}$ and $\sum Mc = Mc1+Mc2$
Where ,
M_{bs} = moment of resistance in sagging
M_{bh} = moment of resistance in hogging

The variousInternational seismic design code reveals significantdifference in SCWB design requirements. American Concrete Institute ACI 318-14 (2014) defines1.2 SCWB ratio .The Canadian Standards Association (CSA, 2004) suggests 1 SCWB ratio .Eurocode 8, 2004 definesa 1.3 SCWB ratio.
Haselton et al. (2011) calculated probability of structures by carrying out IDA on RC frames,considering different heights of building i.e 1-20 storey.They found out 1.2 ratio to be suitable for low rise building(4-storey) but for 12 storey and high rise buildings, ratio above 1.2 may reduce collapse mechanism and this performance will improve upto SCWB ratio of 3.Durrani& Wight (1985) carried out a study to evaluate the performance of interior joints.After the study is carried out a minimum column to beam moment capacity ratio of 1.5 was found to be suitable for design.Medina (2005) worked on 9 - 18 storey RC framestructures and the results of their study showsfor column to not fail, aSCWB ratio of 3 is required.Kirsten Cagurangan (2015) suggested that with increase in height, increase of SCWB ratio is not found to be satisfactory.
Primary objective of present study is to calculate seismic behavior of RC frames designed considering different SCWB ratio and its fragility analysis in order to get an idea about suitable SCWB ratio ranging from 1.2 to 1.8 on 2-storey RC frame structure by comparing collapse probability of each structures.

Details of 4-storey RC building

Two dimensional special moment resisting RC frame building is chosen for this study. 2-storey building is considered. A regular plan having 4 bays, of 4.5m in each direction is shown in fig. 1 .For the consideredbuilding model, the storey height of3.5 m is considered. Slab thickness is considered as 0.15m for all stories. Cross section of columns and beams are assumed to be 0.375m*0.375m and 0.25m*0.4m respectively. Live load on roof and floor is 4kN/$m^2$and floor finish is1kN/m^2. Unit weight of concrete and masonry are 25kN/m^3 and 18kN/m^3 respectively.The building is situated in seismic zone IV and medium soil type. Building is analysed as bare frame model. Stiffness of walls and slab is ignored, however only masses of infills is included in models.The building models are generated using ETABS 2016 (CSI 2016). All the parameters considered for the design are given in table 1.

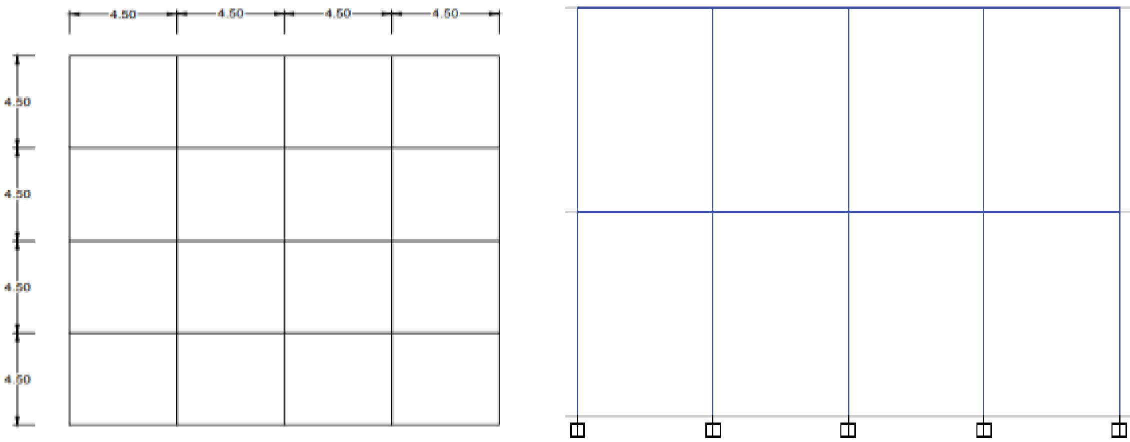


Fig. 1 Plan and Elevation of 4-story RC frame

Table 1: *Design parameters*

Each storey height	3.5 m
Intensity of wall load on floor	2 kN/m^2
Intensity of wall load on roof	1 kN/m^2
Thickness of slab	0.15 m
Floor finish	1 kN/m^2
Live load	4 kN/m^2
Base width	18m
Size of beam	0.250*0.400 m
Size of column	0.375*0.375m
Spacing between grid lines	4.5m

Seismic load calculation

Evaluation of seismic design base shear:

First calculating lump mass at the story level and calculate total seismic weight (Wh)

$$Vb = \frac{Z*I*Sa*W}{2*R*g},$$

Z = Seismic Zone factor (as per Table 3)
I = Importance factor
R= Response reduction factor
$S_{a/g}$ = Design acceleration coefficient

Vertical distribution of Base Shear at each floor (Qi)

$$Qi=\frac{Wi\,Hi^2}{\sum_{j=1}^{n} Wj\,Hj^2}V_b$$

Where,

Qi = Design lateral force at floor i.
Wi = Seismic weight at floor i.
hi = Height of floor I measured from base.

Table 2: *Seismic parameters*

	value
Z (ZONE FACTOR)	0.24
I (IMPORTANCE FACTOR)	1
Sa/g	2.5
R(RESPONSE REDUCTION FACTOR)	5
Ta	0.323

The calculation of seismic base shear and corresponding lateral forces on the buildings are summarized in table 3.

Table 3 :*Lateral load distribution*

Floor	$\mathbf{W_i}$	$\mathbf{H_i}$	$\mathbf{W_iH_i^2}$	$\mathbf{Q_i}$
2	870.34	7	42646.36	85.34
1	933.34	3.5	11433.46	22.88
		∑	504080	108.22

Design of 2-storey RC frame

Typical 2-story symmetric RC frame building shown in Figure 1 was analyze and designed considering all possible load combination according to Indian code of practice IS 456-2000, IS1893-2016 and IS 13920-2016. Reinforcement details of beams and columns of 2-story RC frame considering different SCWB ratio is given in table 4.

Table 4: *Reinforcement details of RC frames*

Frames with SCWB ratio	**members**	**story**	**Width (mm)**	**Depth (mm)**	**Reinforcement details**
1.2 (B2-1)	beam	1-2	250	400	4– 16 #(top) + 3 – 16 # (bottom)
	column	1-2	375	375	8– 16# (uniformly distributed)
1.4 (B2-2)	beam	1-2	250	400	4 – 16 #(top) + 3 – 16 # (bottom)
	column	1-2	375	375	4-20# +4– 16# (uniformly distributed)
1.6(B2-3)	beam	1-2	250	400	4– 16 #(top) + 3 – 16 # (bottom)
	column	1-2	375	375	8– 20# (uniformly distributed)
1.8(B2-4)	beam	1-2	250	400	4 – 16 #(top) + 3 – 16 # (bottom)
	column	1-2	375	375	4– 20#+8-16# (uniformly distributed)

Moment capacity of beam and column is calculated according to IS-456:2000 .Calculation for1.2 moment capacity ratio is shown in table 5 .

Table 5: *Moment capacity of beam*

	Mu (sagging) kNm	**Mu (hogging) kNm**
Top bars	3 – 16 #	4-16#
Bottom bars	4- 16 #	3- 16 #
Ast (mm^2)	804.24	603.18
Asc (mm^2)	603.18	804.24
C1 = 0.36fckbXu=Axu	2250Xu	2250Xu
C2= Asc*fsc	665.405	443.59

T= 0.87fyAst	453.71	680.58
Xu=(T-C2)/A	Negative i.e Xu< d' under reinforced	105.33 mm
Muc1=C1 * (d-0.42Xu)	-	71.28
Muc2 = Asc*fsc(d-d')	-	138.84
Mu= 0.87fyAst (d-d')	142.92	-
Mu= Mu1+ Mu 2 (kNm)	142.92	211

Moment capacity of column

	Column 1	Column 2
d' (mm)	30	30
Ast(mm^2)	2412.74	2412.74
P	2412.74	2412.74
b(mm)	400	400
D(mm)	400	400
Pu (kN)	905	671
d'/D	0.08	0.08
p/fck	0.12	0.12
Pu/fckbD	0.26	0.19
Chart value	0.17	0.17
Mu (kNm)	224.12	224.12

Pushover analysis of RC frames

The 2-dimensional interior RC frame is analyzed using the nonlinear static pushover analysis (NSPA) to obtain the capacity/pushover curve. First pushover analysis is done for the gravity load under force controlled load. Later the subsequent lateral pushover load case is defined to start from final conditions of gravity pushover load case. The lateral force distribution is applied as per Equivalent static analysis. Program defined plastic hinge properties as per the table given in ASCE 41-13 is taken into account for various members in RC frames. P-M_2-M_3 hinge and M_3 hinge was assigned at the both ends of the columns and beam respectively.

Performance point is obtained as per IS-1893:2016 spectra, according to designed seismic zone and soil type.

Fragility analysis

Seismic fragility is defined as the tendency of a building to not perform satisfactorily under a predefined limiting state during an earthquake. There are two by products of seismic fragility analysis:fragility curve and damage probability matrix . In this present study, spectral displacement is taken into consideration. Probability of exceedance is plotted against spectral displacement. Here, HAZUS methodology of HAZUS-MH 2.1 are used for RC building. According to HAZUS method , it is given as follows:

$$P[ds/S_d] = \Phi[\frac{1}{\beta ds} \ln\left\{\frac{Sd}{Sd,ds}\right\}] \quad [1]$$

Where, $S_{d,ds}$= median value of spectral displacement at which the building reaches the threshold of the damage state, ds,β_{ds}= standard deviation of the natural logarithm of spectral displacement of damage state, ds, which is obtained according to building type and height, taken from HAZUS - MH 2.1 and Φ is the standard normal cumulative distribution function.

For developing fragility curves, four damage state are considered. Barbat et. al. have defined four damage state thresholds in terms of yield displacement (D_y) and ultimate displacement(D_u). They are slight damage, moderate damage, severe damage and complete damage as described in table 6.

Table 6 :*Damage state thresholds*

Damage state thresholds	Damage state	Damage grade
S_{d1}=0.7 S_{dy}	Slight	DG1
S_{d2}= S_{dy}	moderate	DG2
S_{d3}= S_{dy} + 0.25 (S_{du} - S_{dy})	Severe	DG3
S_{d4} = S_{du}	Complete	DG4

Fragility curves generated from this method is shown in figure 3.Based on the obtained fragility curves, probability of collapse is calculated. A weighted averagedamage index, DSm, can be calculated as:

$$DS_m = \sum ds_i P[ds_i] [2]$$

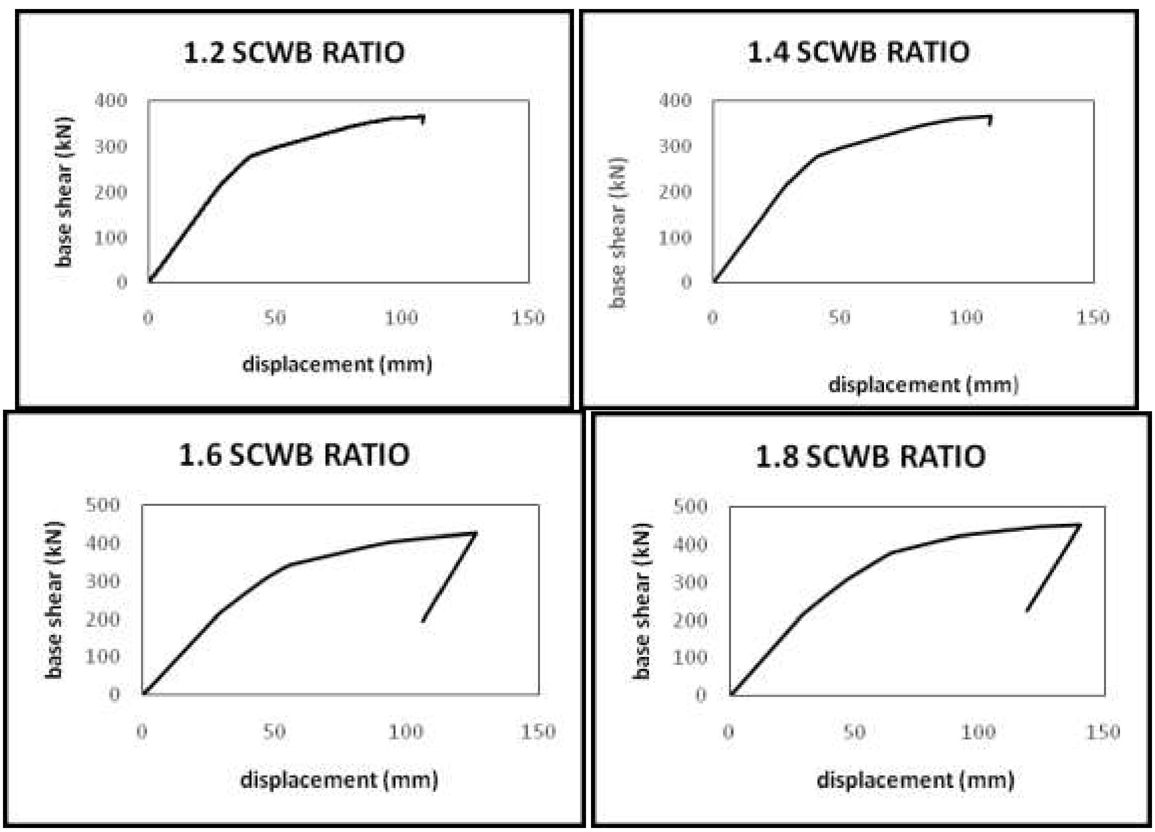
where dsitakesthe values 0, 1, 2, 3 and 4 for the damagestates i considered in the analysis and $P[ds_i]$ are thecorresponding probabilities of exceedance . $DS_m$is close tothe most likely damage state of the structure. Table 7 describes the most probable damage grade as a function of theaverage damage index.

Table 7 :***Damage states and mean damage index value***

Mean damage index intervals	More probable damage state
0-0.5	No damage
0.5-1.5	Slight damage
1.5-2.5	Moderate damage
2.5-3.5	Severe damage
3.5-4	Complete damage

Results and discussions:

Pushover curve is plotted as displacement vs. base shear , shown in figure 2.



- Fig. 2 Pushover Curve Of 4-Storey RC Frame Designed For 4 Different Ratio

Based on pushover curve, yield and ultimate displacement are obtained as shown in table 8.

Table 8 :*Yield and ultimate displacement of RC frames*

RC frames	**Yield displacement, D_y (mm)**	**Ultimate displacement, D_u (mm)**	**Ductility ratio(μ)**	**Spectral displacement, S_d (mm)**
B2-1	35.6	89.45	2.51	53.3
B2-2	35.73	73.16	2.05	53.3
B2-3	39.692	73.068	1.84	55.26
B2-4	39.54	73.18	1.85	58.03

Performance point is plotted in terms of spectral acceleration vs. spectral displacement (Sa vs. Sd) , whose value is taken as per FEMA 440. The performance point calculation as per IS 1893 spectra for zone IV and medium soil type for this study.

Table 9shows the median spectral displacement for slight, moderate, extensive, complete damage states of 2-storey RC building for different SCWB ratio , calculated considering damage threshold

Table 9 :*Median spectral displacement for different damage grade*

RC frames	**Median spectral displacement Sd (mm)**			
	DG1	DG2	DG3	DG4
B2-1	24.92	35.6	49.02	89.45
B2-2	25.011	35.73	45.08	73.16
B2-3	27.78	39.69	48.03	73.068
B2-4	27.68	39.54	47.95	73.18

Fragility curves have been developed for 2-storey RC building and shown in Fig. 3.

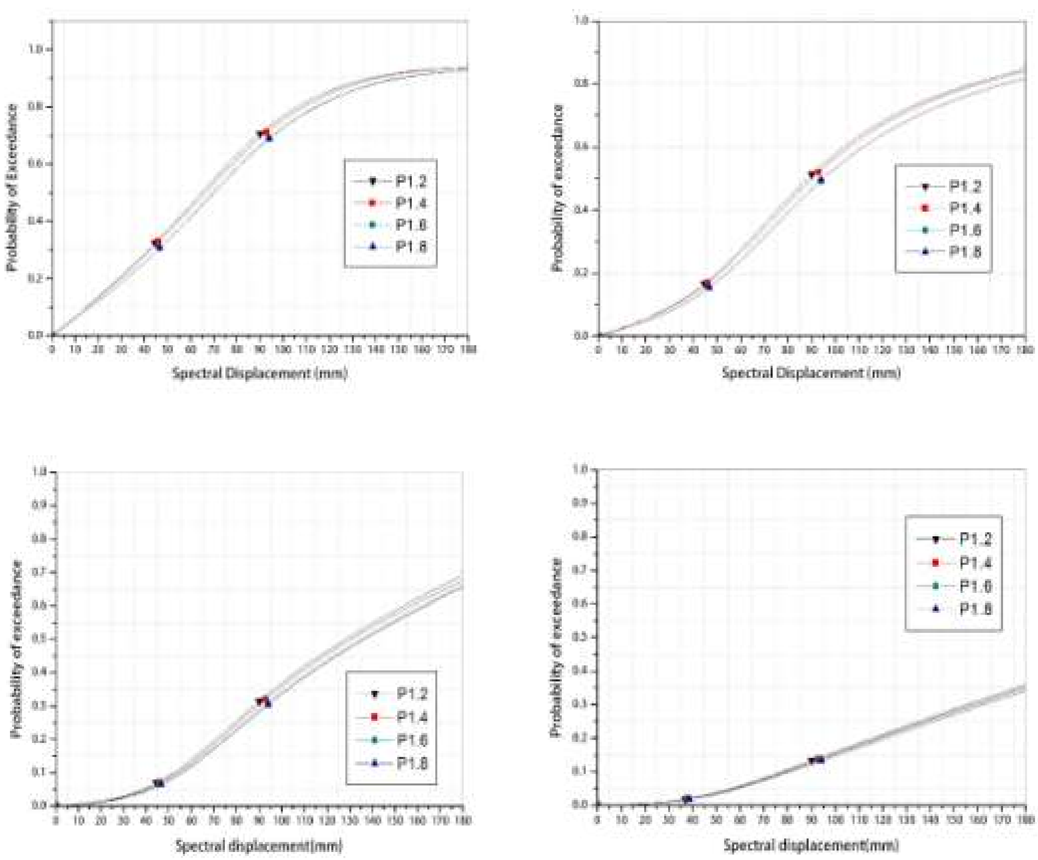


Fig. 3 fragility curves of RC frame considering four damage state

P1.2 = probability of exceedance of B2-1
P1.4 = probability of exceedance of B2-2
P1.6 = probability of exceedance of B2-3
P1.8 = probability of exceedance of B2-4

Results shows that for 90 mm spectral displacement for B2-1 building , the probability of exceedance for slight damage is 71%, 52% for moderate damage, 32 % for severe damage, 16% for complete damage. Similarly, for 93 mm spectral displacement for B2-2 building , the probability of exceedance for slight damage is 70%, 52% for moderate damage, 32 % for severe damage, 13% for complete damage. For spectral displacement of 94 mm for B2-3 building , the probability of exceedance for slight damage is 68%, 43% for moderate damage, 30 % for severe damage, 13% for complete damage. For spectral displacement of 94 mm for B2-4 building , the probability of exceedance for slight damage is 68%, 43% for moderate damage, 30 % for severe damage, 13 % for complete damage.

For each building type , damage probability matrices (DPM) is obtained. The damage probabilitymatrices of present buildings is calculated in table 10 .$DS_m$is calculated using equation (2). As observed from table10 ,all RC frames ranging from 1.2 SCWB ratio to 1.8 SCWB ratio shows moderate damage state . There is no major difference in their performance.

Table 10 :*Damage probability matrices and more probable damage state for RC building considering DBE*

RC frames	**Damage state probabilities**				**Weighted mean damage state (DS_m)**	**More probable damage state**
	DG1	DG2	DG3	DG4		
B2-1	0.349	0.313	0.266	0.2804	2.24	Moderate damage
B2-2	0.359	0.323	0.2381	0.3763	2.34	Moderate damage
B2-3	0.325	0.312	0.2025	0.3768	1.97	Moderate damage
B2-4	0.343	0.300	0.2102	0.392	2.13	Moderate damage

Conclusions

Ductility ratio decreases going from 1.2 ratio to 1.8 ratio, which means structure becomes less ductile .Alsono further improvement in terms of hinge formation is seen going from 1.2 SCWB ratio to 1.8 SCWB ratio.Performance of B2-1 (i.e RC frame with 1.2SCWB ratio is found to be satisfactory, as column hinges at the top story doesn't reaches collapse prevention (CP). Considering economy of the structure and also the performance of structure during earthquake, SCWB ratio of 1.2 is found to be satisfactory for 4-storey RC frame.

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