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ORIGINAL PAPER

Influence of Effective Stiffness on Seismic Response of RC Frame Building with Shear Walls

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Abstract

Purpose This article aims to explore the implication of effective stiffness modifiers of structural elements on the seismic performance of high-rise RC frame buildings with shear walls.

Contribution and method Effective stiffness of structural elements i.e., beams, columns, shear walls etc. plays a pivotal role in the seismic evaluation of Reinforced Concrete (RC) shear wall buildings which are predominantly considered through the use of stiffness modifiers in Indian design standards like various national design standards worldwide. The reduction in stiffness of the structural members is mainly due to crack formation in members due to shrinkage, creep, bond-slip of the reinforcement, etc. which further aggravates due to large inelastic deformation caused by seismic events. stiffness modifiers for various structural members i.e., beams and columns have been recommended in revised Indian seismic standards (BIS inIS 1893 (Part 1)—2016 Indian Standard criteria for earthquake resistant design of structures, part 1: general provisions and buildings (fifth revision). Bureau of Indian Standards, New Delhi, 2016), however specific guidelines for the same are missing for RC shear walls. This paper presents a comprehensive review of the available effective stiffness recommendation by various national seismic design standards viz., ASCE (ASCE-41 in ASCE/SEI 41-17, seismic evaluation and retrofit of existing buildings. American Society of Civil Engineers, Reston, 2017), Eurocode (Design of structures for earthquake resistance—part 1: general rules, seismic actions, and rules for buildings, 2005), New Zealand code (NZS in NZS 3101:2006 New Zealand Standard Concrete Structures Standard, 2006) and assess the influence of effective stiffness on seismic evaluation of high-rise RC shear wall buildings. It is observed that a significant difference in peak strength is observed with variation in stiffness modifiers of beam and column, whereas their peak strength is not significantly sensitive to the effective stiffness of shear walls due to the higher stiffness of shear walls compared to other structural elements.

Conclusion It has been observed that the choice of stiffness modifiers of structural elements influences the seismic performance of RC shear wall buildings in terms of strength, stiffness and plastic deformation capability. Indian seismic design standard BIS (2016) does not prescribe any reduction in gross stiffness to get effective stiffness of shear walls and it is evident from the parametric study that the influence of effective stiffness of the shear wall on the seismic performance of the RC shear wall building is negligible whereas the effective stiffness of beams and columns has a profound effect on seismic behaviour of such buildings.

Keywords RC shear wall · Effective moment of inertia · Stiffness modifiers · Seismic performance

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Abbreviations

ASCE	American Society of Civil Engineers
BIS	Bureau of Indian Standard
D_u	Ultimate displacement
D_y	Yield displacement
EI	Flexural stiffness
I	Moment of inertia
NZS	New Zealand Standard
RC	Reinforced concrete
SMRF	Special moment resisting frames
TS	Turkish Standards

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V_u Peak strength
V_y Yield strength

Introduction

The effective stiffness of the structural members like beams, columns, shear walls etc. play an important role in the seismic performance of Reinforced Concrete (RC) buildings and the consequence of effective stiffness on overall seismic performance of RC buildings is generally captured through the use of stiffness modifier during analysis. Effective flexural stiffness of the structural members depends on many parameters such as the loading conditions, end restraints, cracking, creep, and nonlinear properties of the material i.e., nonlinear portion of the stress–strain curve of the material [24]. The stiffness of members is expected to be reduced when members are subjected to various types of loading when it can't be recovered to its original uncracked section stiffness. Dynamic structural properties like the fundamental period, and response quantities of the building such as force distribution, deformation demands, yield, and ultimate displacement of the building are the major parameters that will be affected by the actual effective stiffness of the structural members [15, 25]. Therefore it is necessary to estimate the accurate stiffness modifiers for prescriptive seismic design of buildings [31].

Many national building design standards proposed effective stiffness values for various structural members. Indian seismic design standard BIS [6] was silent about the effective stiffness of the structural member. However, the latest revised Indian seismic design standard BIS [8] recommended stiffness modifiers for beams and columns but not for the shear walls. Indian standard BIS [10] for the structural safety of tall buildings recommended cracked section properties for walls and slabs which are not present in the seismic design standard BIS [8]. Bonet et al. [11] proposed analytical expressions to estimate the stiffness modifiers of the columns of any shape subjected to a combination of axial load and biaxial bending moments due to either short-time loads or sustained loads based on experimental observations where effective stiffness of the member is a function of the effective cross-section dimensions and strength properties of the constituent materials of column i.e., grade of concrete and steel. As effective stiffness of the structural members also depends on the various parameters like prestressed/non-prestressed, axial load ratio, thereby many international standards provide different stiffness modifiers for various structural members. ASCE/SEI [2] recommended flexural stiffness of RC beams as 0.3 whereas depending on the axial load ratio, effective stiffens of column varies from 0.3–0.7. Flexural stiffness of reinforced masonry wall is based on the cracked section property where the moment of inertia of cracked section shall be considered as 50% of the gross moment of inertia of the section. The effective stiffness of the structural members recommended in various national design guidelines is summerized in Table 1. Indian standard BIS [7] recommends considering cracked section properties of structural elements for seismic evaluation of existing buildings and suggests obtaining stiffness modifiers by the rational procedure.

Several studies have been undertaken in the past to understand the importance of appropriate stiffness of structural members or to predict the effective stiffness of structural members such as beam, column etc. Gondaliya et al. [19] conducted a study on seismic collapse probability of two-, four-, eight-, and twelve-storey RC frame buildings designed as per the Indian standard [6] with gross stiffness section properties representing the uncracked section properties and the same set of buildings designed as per revised Indian standard [8] with effective section properties considering the cracked section properties. They have concluded that the seismic collapse probability of the buildings designed using effective section properties is approximately 57% less than the buildings designed using gross section properties of the structural elements. Das and Choudhury [13] studied the importance of considering the effective stiffness of the structural components while performing the nonlinear analysis to evaluate the seismic performance of the buildings. They have concluded that buildings analyzed with uncracked section properties exhibit very conservative drift and higher performance levels than those buildings with effective stiffness properties considering cracked section properties based on strength.

Das and Choudhury [14] conducted a study to predict the effective stiffness of the RC columns using a support vector regression approach. Prajapati and Amin [28] conducted a study on a set of RC buildings by performing pushover analysis and nonlinear time history analysis. They have concluded that RC frames designed with gross section property

Table 1 Review of stiffness modifiers considered in various national design standards

Member	Construction of new buildings				Existing buildings	Tall buildings
	BIS [6]	BIS [8]	ASCE/SEI [2]	Eurocode [17]	BIS [7]	BIS [10]
Beam	–	0.35 *EI*	0.30 *EI*	0.50 *EI*	0.50 *EI*	0.35 *EI*
Column	–	0.70 *EI*	0.70 *EI*	0.50 *EI*	0.70 *EI*	0.70 *EI*
Shear wall	–	–	0.50 *EI*	0.50 *EI*	0.50 *EI*	0.70 *EI*

meet inter-storey drift limits, while those using effective section properties exceed limits. Kwon and Ghannoum [23] conducted an experimental study to derive the lateral stiffness of RC frame shear wall buildings and concluded that larger stiffness values for shear walls are mentioned in major national standards than the experimental values. Ramos [32] carried out an analytical study on a set of RC frame buildings to evaluate their seismic response by varying gross stiffness properties of the structural elements and concluded that a reduction in stiffness leads to increase in time period and drift parameters.

It can be concluded from the review of existing literature that building will have a significantly lengthened fundamental time period when the stiffness modifiers of various structural elements like beams, columns, and shear walls are being considered than the building analyzed without any stiffness modifiers i.e., with gross stiffness (I_g). Besides, lengthened fundamental time period, stiffness of the structural members largely influences seismic demand, floor drift and absolute roof displacement of the building. Therefore, it is necessary to estimate accurate stiffness modifiers of various structural elements for realistic assessment of building period and thereby seismic forces. However, the stiffness modifiers are important and influence the behavior of structures that are subjected to dynamic loads such as earthquakes and wind loads and not the structres subjected to gravity loads only because the extent of cracking of major structural members is negligible under static loads. Although the past studies concentrated on estimation of effective stiffness for various structural members or the extent of its influence on explicit structural properties, however, a comprehensive scientific study of the influence of effective stiffness of various structural members such as beam, column, shear wall on the overall seismic behaviour of RC frame building with shear wall which is a very common structural configuration for multistorey residential building in urban India. In the present study, an attempt has been made to evaluate the individual and compound effect of stiffness modifiers of various structural members (beam, column and shear wall) on the seismic performance of a high-rise (12-storey) RC shear wall building by performing nonlinear static analysis. Seismic performance is evaluated by comparing the yield and ultimate displacements, plastic deformation capacity as well as strength parameters.

Parametric Study

The considered high-rise (12-storey) RC frame building with shear wall is shown in Fig. 1. The storey height is 3.3 m and is designed as Special Moment Resisting Frames (SMRF) with ductile shear walls as per relevant Indian standards [8, 9]. The front elevation view and side elevation view of the considered building are shown in Fig. 2a and b respectively.

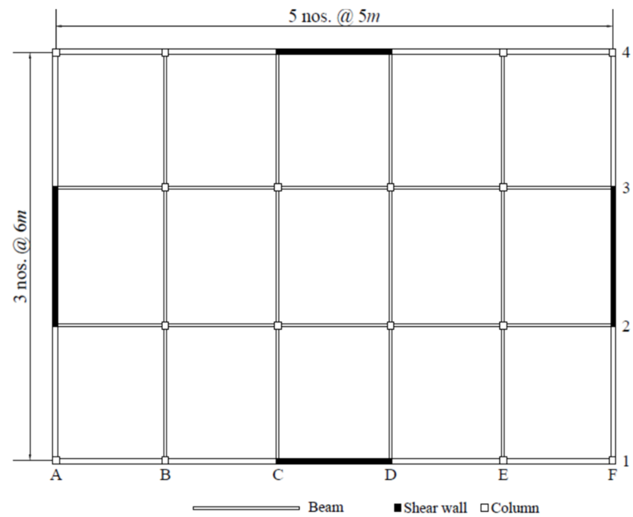

Fig. 1 Plan view of the considered RC shear wall building

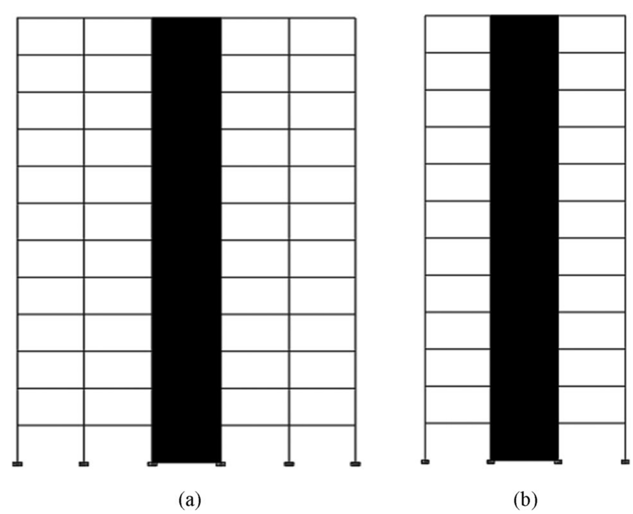

Fig. 2 Elevation of the considered buildings. **a** Longitudinal direction and **b** transverse direction

Shear wall plays a significant role during seismic events by preventing severe damage to RC shear wall buildings even if the seismic response of the beams and columns is poor [27]. The RC shear walls are provided in a symmetric location in the plan to avoid the complex behaviour of RC shear wall building due to asymmetrical placement of shear wall leading to torsion [33]. The RC shear walls are also extended throughout the elevation of the buildings, as the location of shear wall significantly influences the seismic performance of the buildings [12, 33].

M30 grade of concrete (characteristic compressive strength of 30 MPa) and Fe500 grade of rebar are being considered for the study. Dead loads and imposed loads are applied to the building at storey level as per the Indian standards BIS [3, 4]. The weight of infill walls is applied to the corresponding beams considering the prevalent practice of 115 mm internal and 230 mm external wall thickness [20, 22] in India. The building is designed for load combinations prescribed by relevant Indian design standards [5, 8] assuming an importance factor of 1.5 and all the representative buildings are considered to be situated in seismic zone-IV (peak ground acceleration of 0.24*g*) on soil type-II [8]. Design and modelling parameters of the considered buildings are presented in Table 2.

The beams and columns are modelled using 3D frame elements and shear walls as shell elements in ETABS software [16]. The dynamic properties of all the considered building presented in Table 3 through modal analysis shows that 75% and above mass participation in the fundamental mode of all considered buildings satisfying the nonlinear static procedure criteria ASCE-41 [1] and FEMA-356 [18] for nonlinear evaluation of the considered buildings.

Table 2 Design and modelling parameters of the considered building

General	Design level		RC frame building with shear walls
	No. of stories		12-storey, storey height 3.3 m
Material	Concrete		M30
	Steel		Fe500
Loading	Dead load		Self-weight of members Weight of infill Weight of slab and floor finish Weight of 1 m high and 230 mm thick masonry parapet wall
	Live load		4 kN/m^2 on corridor and 3 kN/m^2 on other floor area
	Load Combinations		1.5 (dead load + live load) 1.2 (dead load + live load ± earthquake load) 1.2 (dead load ± Earthquake load) 0.9 dead load ± 1.5 earthquake load
Structural modeling	Software used		ETABS [16]
	Structure model		3D space frame model
	Element model		3D line elements for beams and columns Slabs as rigid diaphragm Shear walls using shell element
	Plasticity model		Lumped plasticity model ASCE-41 [1]
	P-delta effect		Considered in analyses
Sections	Beams		400 mm × 450 mm
	Columns	Ground to 4th floor	500 mm × 500 mm
		5th floor to 8th floor	450 mm × 450 mm
		9th to roof	400 mm × 400 mm
	Shear wall		400 mm

Table 3 Dynamic properties of the considered buildings

S. no.	Building model	Naturalfundamental time period of the analytical model (Sec.)	Mass participation factor in first mode (%)
1	0.1B 0.1C	2.234	76.2
2	0.1B 0.2C	2.228	77.0
3	0.1B 0.3C	2.224	75.8
4	0.1B 0.4C	2.217	75.2
5	0.1B 0.5C	2.212	76.5
6	0.1B 0.6C	2.208	76.1
7	0.1B 0.7C	2.198	75.4
8	0.1B 0.8C	2.192	76.9
9	0.1B 0.9C	2.186	77.1
10	0.1B 1.0C	2.182	76.6

Nonlinear static analysis has been carried out by assigning M2-M3 hinges at both ends of beams and P-M2-M3 hinges at both ends of columns [2]. The nonlinear behaviour of shear walls has been considered by introducing fiber P-M3 hinges to the shell elements.

Effect of Stiffness of Structural Elements on Fundamental period

The fundamental period of the buildings depends on the mass and stiffness of the buildings. The moment of inertia of the structural components majorly depends on the cross-section dimensions of the structural components of buildings. During seismic events, the buildings may be subjected to cracking, and thereby reduction in stiffness takes place, hence, stiffness modifiers need to be considered for all structural components of the buildings while analysing the building for lateral loads. Figure 3 show a comparison of the fundamental period of a 12-storey RC shear wall building with varying stiffness modifiers of the beams and columns. It is observed that the reduction in the gross stiffness of the structural components leads to an increase in the fundamental period of the buildings. Time period is inversely proportional to the stiffness of the structural components. The reduction in the fundamental period of the building leads to flexible buildings thereby these buildings have a higher fundamental period than the buildings without stiffness reduction of the structural components.

Effect of Stiffness of Structural Elements on Seismic Behaviour and Capacity Curve Parameters

Figure 4a–d shows capacity curves of 12-storey RC frame buildings with various combinations of effective stiffnesses of beams and columns. The effective stiffness of beams is varied as $0.1I_g$, $0.2I_g$,$0.3I_g$ and $0.4I_g$, whereas stiffness modifiers of the column vary from $0.1I_g$ to $1I_g$. The load-deformation behaviour of buildings with various combinations of effective stiffnesses of beams and columns are thereafter

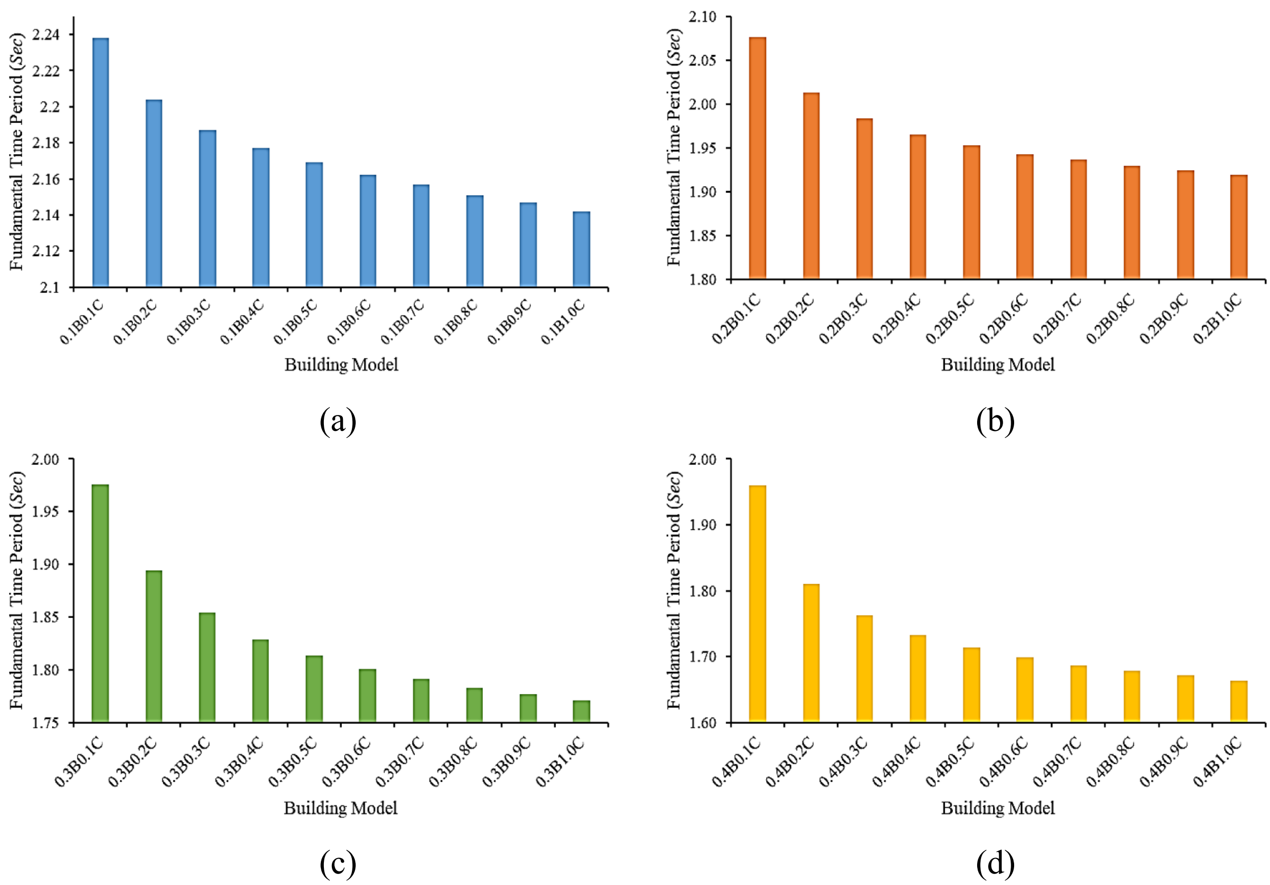

Fig. 3 Comparison of fundamental period of representative building for various effective stiffnesses of column with variation of effective stiffness of beam as **a** $B=0.1I_g$; **b** $B=0.2I_g$; **c** $B=0.3I_g$; **d** $B=0.4I_g$. In the above figures, prefix of 'B' signifies effective stiffness value of beams while prefix of 'C' signifies effective stiffness value of columns

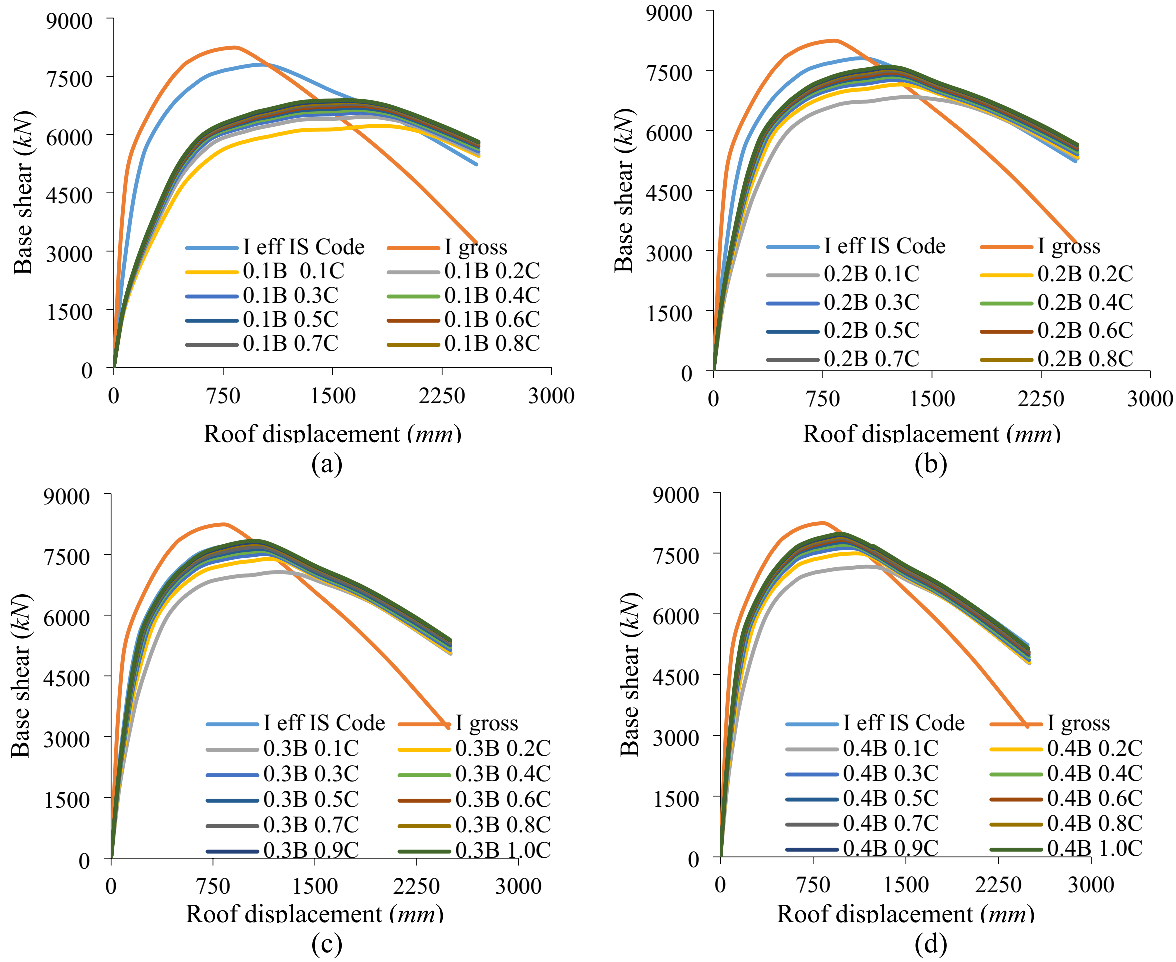

Fig. 4 Effect of varying effective column stiffness on capacity curve with constant stiffness of beam as **a** $0.1I_g$, **b** $0.2I_g$, **c** $0.3I_g$, **d** $0.4I_g$. In the above figures, prefix of 'B' signifies effective stiffness value of beams while prefix of 'C' signifies effective stiffness value of columns

compared with capacity curves obtained for stiffness modifiers recommendations of Indian seismic standards [6, 8]. The variation in effective stiffness of the beams from $0.1I_g$ to $0.4I_g$ is chosen based on the effective stiffness recommendations of beams prescribed in various national design standards as presented in Table 1. The seismic response of the columns plays a pivotal role in the global failure of RC frame building. Accordingly, to capture the implicit contribution of column stiffness on the seismic performance of the 12-storey RC frame building, the effective stiffness of columns is varied from $0.1I_g$ to $0.9I_g$.

Priestley [29–31] and other researchers have pointed out that force is a poor indicator of damage, and there is no clear relationship between strength and damage. Hence, force cannot be the sole criterion for design, whereas displacement capacity is more fundamental to damage control [29]. However, the inelastic deformation effects are indirectly accounted for using the Response Reduction Factor in the traditional Force-Based Design concept adopted by Indian code design practices. Accordingly, the displacement parameters like yield displacement (D_y), ultimate displacement (D_u), and plastic deformation (D_p) have been estimated as suggested by Haldar and Singh [21] along with yield strength (V_y), peak strength (V_u) for all the considered buildings and is presented in Figs. 5 and 6. Table 4 summarizes the response quantities for all the representative buildings.

The peak strength of the building with an effective stiffness of $0.1I_g$ for beams and $0.1I_g$ of columns is 19% lesser than the same building with the gross moment of inertia of structural members, whereas the building with an effective stiffness of $0.1I_g$ for beams and $1.0I_g$ of columns is 11% lesser than the same building with the gross moment of inertia of structural members (Fig. 6). This difference is due to change in effective stiffness of columns which affects the overall stiffness of the building. As the effective stiffness of the columns increases, the structure becomes stiffer thereby it will have higher peak strength than the building with structural elements having lower effective stiffness.

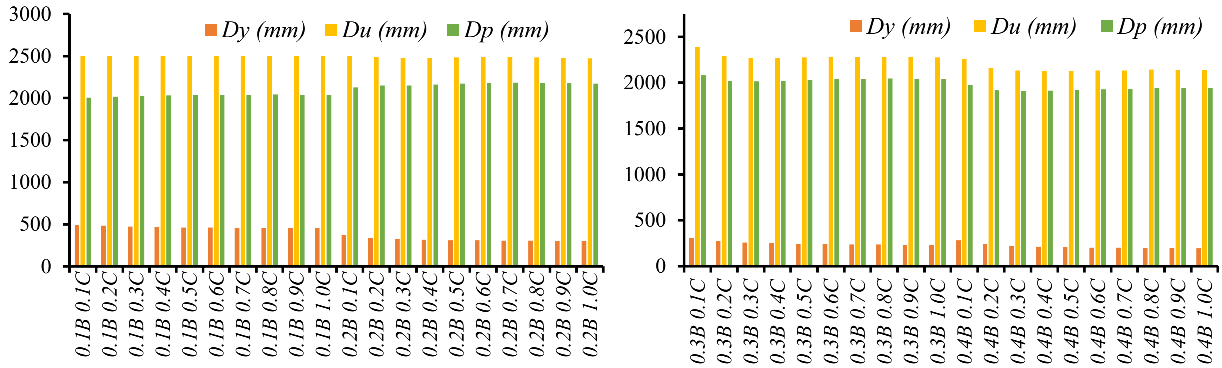

Fig. 5 Variation of yield (D_y) and ultimate (D_u) displacement; and plastic deformation (D_p) response quantities corresponding to various effective stiffness combinations of beams and columns. Prefix of 'B' signifies effective stiffness value of beams while prefix of 'C' signifies effective stiffness value of columns

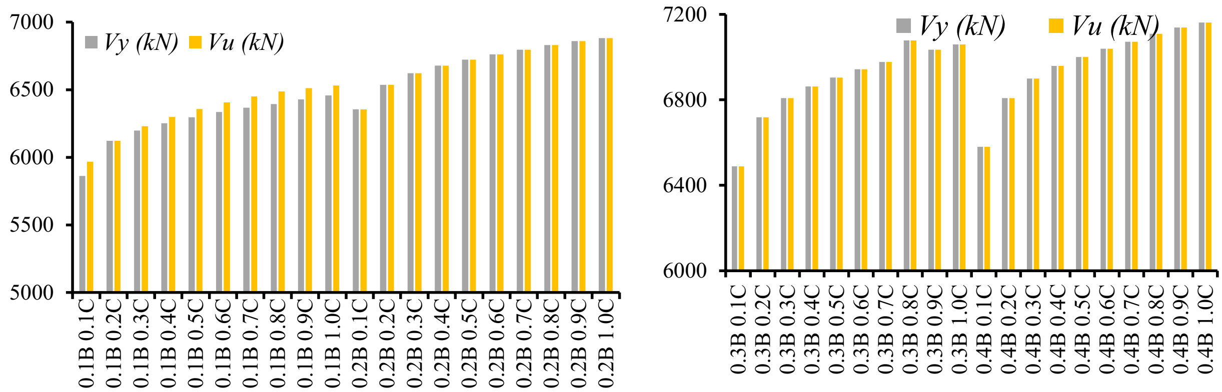

Fig. 6 Variation of yield (V_y), and ultimate shear force (V_u) corresponding to various effective stiffness combinations of beams and columns. Prefix of 'B' signifies effective stiffness value of beams while prefix of 'C' signifies effective stiffness value of columns

Similarly, the yield strength of the 12-storey building with an effective stiffness of $0.3I_g$ for beams and $0.1I_g$ of columns is 12% lesser than the same building with gross moment of inertia of structural members, whereas the building with an effective stiffness of $0.3I_g$ for beams and $1.0I_g$ of columns is 4% lesser than the same building with gross moment of inertia of structural members (Fig. 6, Table 4). The change in the effective stiffness of the columns affects significantly than the change in the effective stiffness of the beams because columns are the one of major lateral force-resisting structural components in the buildings after the shear wall.

The ultimate displacement of the 12-storey building with an effective stiffness of $0.3I_g$ for beams and $0.1I_g$ of columns is 46% more than the same building with gross moment of inertia of structural members, whereas the building with an effective stiffness of $0.3I_g$ for beams and $1.0I_g$ of columns is 39% more than the same building with gross moment of inertia of structural members. The yield displacement of the 12-storey building with an effective stiffness of $0.3I_g$ for beams and $0.1I_g$ of columns is 159% more than the same building with gross moment of inertia of structural members, whereas the building with an effective stiffness of $0.3I_g$ for beams and $1.0I_g$ of columns is 95% higher than the same building with gross moment of inertia of structural members. It is evident from Figs. 5, 6 and Table 4 that the capacity curve parameters i.e., yield and ultimate displacement and strengths are sensitive to the effective stiffness of both beams and columns. Columns are the major lateral force-resisting structural elements in the RC frame buildings, therefore, change in the effective stiffness of the columns leads to significant differences in the yield, ultimate strength and yield and ultimate displacement of the buildings (Table 4). It can be further observed that as the effective stiffness of the beam increases from $0.1I_g$ to $0.4I_g$ yield and ultimate displacement decrease whereas yield and ultimate strength increase significantly and eventually in combination with 0.4B 0.4C it is closest to the effective stiffness combination of beam and column I_{eff} prescribed by BIS [8].

Shear walls are the major lateral force-resisting structural components in RC shear wall buildings. To evaluate the explicit influence of the effective stiffness of the shear wall on overall seismic performance of high-rise (12-storey)

Table 4 Influence of effective stiffness of beams and columns on capacity curve parameters of considered buildings

Model nomenclature	D_y (mm)	D_u (mm)	V_y (kN)	V_u (kN)	Model nomenclature	D_y (mm)	D_u (mm)	V_y (kN)	V_u (kN)
I eff [8]	217.1	2204.1	7030.4	7030.4	I eff [8]	217.1	2204.1	7030.4	7030.4
I gross [6]	119.1	1637.1	7360.9	7360.9	I gross [6]	119.1	1637.1	7360.9	7360.9
0.1B 0.1C	493.1	2500.0	5861.1	5966.8	0.3B 0.1C	310.3	2390.5	6489.1	6489.1
0.1B 0.2C	482.1	2499.5	6122.6	6122.6	0.3B 0.2C	274.4	2292.0	6719.0	6719.0
0.1B 0.3C	471.5	2499.0	6197.3	6229.9	0.3B 0.3C	258.5	2272.0	6808.0	6808.0
0.1B 0.4C	466.4	2499.0	6252.5	6297.4	0.3B 0.4C	249.8	2270.0	6863.1	6863.1
0.1B 0.5C	462.9	2499.0	6296.1	6355.8	0.3B 0.5C	244.3	2275.5	6904.6	6904.6
0.1B 0.6C	460.4	2499.0	6334.7	6406.3	0.3B 0.6C	240.7	2281.0	6942.8	6942.8
0.1B 0.7C	458.3	2499.0	6366.7	6449.6	0.3B 0.7C	238.2	2282.5	6977.8	6977.8
0.1B 0.8C	457.6	2499.0	6395.0	6486.1	0.3B 0.8C	236.4	2281.5	7077.5	7077.5
0.1B 0.9C	457.8	2499.0	6427.2	6512.0	0.3B 0.9C	235.0	2279.0	7035.0	7035.0
0.1B 1.0C	458.3	2499.0	6457.0	6531.1	0.3B 1.0C	233.7	2275.5	7059.3	7059.3
0.2B 0.1C	371.6	2500.0	6353.9	6353.9	0.4B 0.1C	281.2	2259.5	6581.1	6581.1
0.2B 0.2C	337.5	2488.0	6534.8	6534.8	0.4B 0.2C	240.8	2160.0	6808.8	6808.8
0.2B 0.3C	323.4	2474.5	6622.6	6622.6	0.4B 0.3C	223.1	2134.0	6900.6	6900.6
0.2B 0.4C	315.6	2477.5	6677.7	6677.7	0.4B 0.4C	213.4	2127.0	6958.5	6958.5
0.2B 0.5C	310.9	2484.5	6721.6	6721.6	0.4B 0.5C	207.5	2128.5	7000.1	7000.1
0.2B 0.6C	307.9	2488.0	6760.9	6760.9	0.4B 0.6C	203.4	2132.5	7039.2	7039.2
0.2B 0.7C	305.8	2488.5	6796.8	6796.8	0.4B 0.7C	200.7	2133.5	7072.1	7072.1
0.2B 0.8C	304.2	2485.0	6828.9	6828.9	0.4B 0.8C	198.9	2144.5	7109.9	7109.9
0.2B 0.9C	302.9	2478.5	6858.3	6858.3	0.4B 0.9C	197.2	2141.5	7138.6	7138.6
0.2B 1.0C	301.9	2473.5	6881.1	6881.1	0.4B 1.0C	195.9	2139.0	7162.5	7162.5

RC shear wall buildings, pushover analyses have been undertaken to generate the capacity curves of RC shear wall buildings with varying effective stiffness of shear wall. As the Indian seismic design standard BIS [8] does not prescribe any reduction in gross stiffness to get effective stiffness of shear walls, the same 12-storey building with effective stiffness of beams and columns as suggested by BIS [8] has been re-analysed with varying effective stiffness of shear walls using stiffness modifiers from 0.1 to 0.9. Capacity curves of the buildings with constant beam-column effective stiffness as per BIS [8] and with varying shear wall stiffness are presented in Fig. 7.

The response quantities such as yield and ultimate displacement and plastic deformation capacities as well as yield and ultimate strength of the representative buildings are presented in Fig. 8a and b respectively. Table 4 summarizes the impact of shear wall stiffness on seismic response parameters of the considered high-rise RC shear wall building. It can be observed from Fig. 8 in conjunction with Table 4 that the peak strength of the 12-storey building with effective flexural stiffness of $0.1I_g$ of shear wall is 6% higher than the same building with gross moment of inertia of structural members, whereas the building with effective flexural stiffness of 1.0Ig of shear wall is 4% higher than the same building with gross moment of inertia of structural members. The change in effective stiffness of the shear wall alone in the building does not affect on peak strength of the RC shear wall building as the beams and columns undergo damage before the shear wall due to its high in-plane stiffness. The yield strength of the 12-storey building with effective flexural stiffness of $0.1I_g$ of shear wall is 6% higher than the same building with gross moment of inertia of structural members, whereas the building with effective flexural stiffness of $1.0I_g$ of shear wall is 4% higher than that of the same building with gross moment of inertia of structural members. The ultimate displacement of the 12-storey building with effective flexural stiffness of $0.1I_g$ of shear wall is 31% higher than the same building with gross moment of inertia of structural members, whereas the building with effective flexural stiffness of $1.0I_g$ of shear wall is 34% higher than the same building with gross moment of inertia of structural members. The yield displacement of the 12-storey building with effective flexural stiffness of $0.1I_g$ of shear wall is 82% higher than the same building with gross moment of inertia of structural members, whereas the building with effective flexural stiffness of $1.0I_g$ of shear wall is 80% higher than the same building with gross moment of inertia of structural members (Table 5). The plastic deformation capacity of the building represents the deformation capacity of the building, there is no significant difference in plastic deformation of the building with

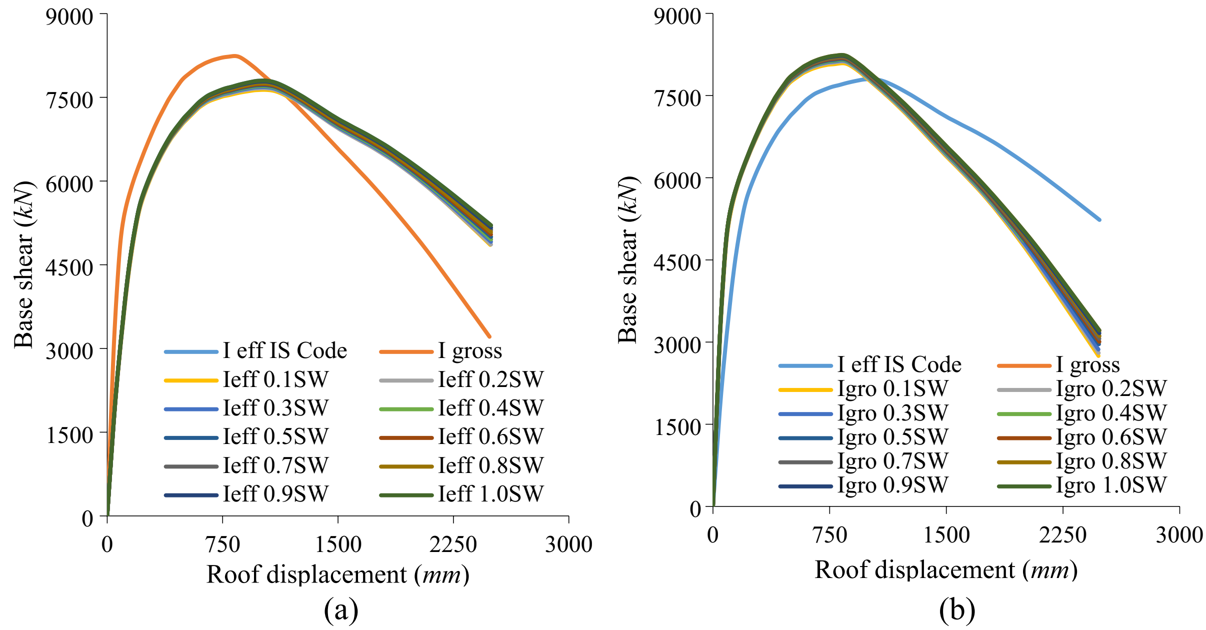

Fig. 7 Capacity curves of 12-storey building with varying stiffness modifiers of shear walls. **a** Effective stiffness of beams and columns and **b** gross stiffness of beams and columns. In the above figures, prefix of 'B' signifies effective stiffness value of beams while prefix of 'C' signifies effective stiffness value of columns

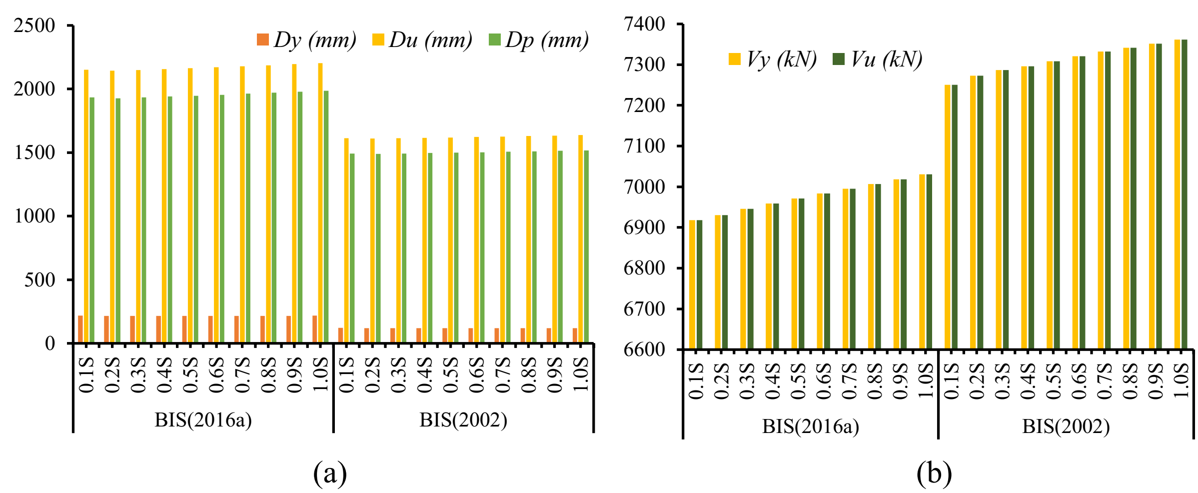

Fig. 8 Variation of response quantities for various effective stiffness of shear wall. Prefix of 'S' signifies effective stiffness value of shear walls. **a** Displacement variation (D_y, D_u and D_p) and **b** base shear variation (V_y and V_u)

the variation of flexural stiffness of shear wall alone as the yielding of the beams and columns occurs before the shear wall.

It can be concluded from Figs. 7, 8 and Table 5 that the capacity curve parameters i.e., yield and ultimate displacement and strengths are not sensitive enough to the effective stiffness of shear walls.

Conclusions

The analytical study of a high-rise RC building with symmetric shear walls shows that the effective stiffness of RC structural elements has a significant influence on the seismic performance of such buildings in terms of strength,

Table 5 Influence of effective stiffness of shear wall on capacity curve parameters of considered building

	Model nomenclature	D_y (mm)	D_u (mm)	V_y (kN)	V_u (kN)
	I eff [8]	217.1	2204.1	7030.4	7030.4
	I gross [6]	119.1	1637.1	7360.9	7360.9
BIS [8]	0.1SW	217.8	2152.0	6917.9	6917.9
	0.2SW	216.0	2143.5	6930.2	6930.2
	0.3SW	215.6	2149.5	6945.6	6945.6
	0.4SW	215.5	2156.0	6958.9	6958.9
	0.5SW	215.7	2163.2	6970.9	6970.9
	0.6SW	215.9	2171.0	6983.4	6983.4
	0.7SW	216.1	2179.0	6995.0	6995.0
	0.8SW	216.4	2187.0	7006.6	7006.6
	0.9SW	216.7	2195.0	7018.4	7018.4
	1.0SW	217.1	2204.0	7030.4	7030.4
BIS [6]	0.1SW	120.9	1612.0	7250.9	7250.9
	0.2SW	119.5	1610.0	7272.8	7272.8
	0.3SW	119.3	1612.5	7287.1	7287.1
	0.4SW	119.2	1615.2	7295.8	7295.8
	0.5SW	119.3	1618.5	7308.3	7308.3
	0.6SW	119.4	1622.5	7320.4	7320.4
	0.7SW	119.5	1626.0	7332.0	7332.0
	0.8SW	119.7	1629.5	7341.7	7341.7
	0.9SW	119.8	1633.5	7351.2	7351.2
	1.0SW	120.0	1637.0	7361.2	7361.2

stiffness and plastic deformation capacity. The effective stiffness of beams and columns recommended by the Indian standard [8] leads to a significant difference in the performance compared to the building with gross stiffness of the structural members. Under seismic excitation structure undergoes large displacement as it experiences a higher lateral force, therefore, to achieve a conservative seismic design of buildings, it is recommended to adapt an appropriate pair of effective section modifiers for the various structural members depending on their relative importance in damage of the overall structure. Indian seismic design standard BIS [8] does not prescribe any reduction in gross stiffness to get effective stiffness of shear walls and it is evident from the parametric study that the influence of effective stiffness of the shear wall on the seismic performance of the considered RC shear wall building is negligible whereas the effective stiffness of beams and columns has a profound effect on seismic behaviour of such buildings. The general design practice is to ignore the impact of effective stiffness for all practical purposes. However, it is of utmost importance for the structural designers to consider the appropriate stiffness modifiers recommended by the respective country standards as stiffness modifiers of RC structural elements have a profound effect on the overall seismic performance of the structure.

Data availability The data used in this study are available upon reasonable request. Researchers interested in aceessing the data should contact the author.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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