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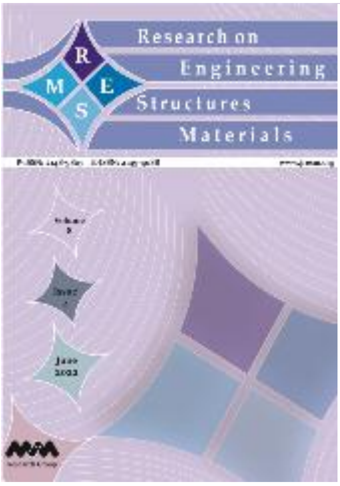

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Research Article

Sensitivity indices of RC beams considering construction sequence analysis for RC high-rise building

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Abstract

Construction Sequence Analysis (CSA) is a technique that simulates real-time onsite construction procedures like timing, sequential loading, and construction sequence. This study compares the bending moment at various sections of beams using the CSA- Construction Sequence Analysis and LSA-Linear Static Analysis methods. Four 40-storeyed RC buildings of different spans are studied to consider the long-term effect of concrete properties like creep and shrinkage. The effects for 30 years from the application of live load in the CSA methods were analysed. It is essential to know the sensitivity of a beam for bending moments concerning the CSA method compared to the LSA method. Knowing how the sensitivity of beams varies concerning span in RC buildings is essential. The study divides beams into five different sensitivity categories. According to the study, the LSA approach provides 3.6% higher to 70.24% lower, 42.29% higher to 111.49% lower, and 17% higher to 44% lower left-end support, right-end support, and mid-span moments, respectively, than the CSA method in beams of normal categories. The study also concluded that RC shear walls increase the sensitivity of surrounding beams. These beams are categorized into the most vulnerable categories among all, and these categories seem absent in a plan without RC walls. The study concludes that it is advisable to adopt the CSA method with time-dependent effects of concrete when designing RC moment frame high-rise buildings. The analysis is done using MIDAS Gen-17 software.

1. Introduction

Structural engineers analyse and design an RC building by simultaneously applying all loads to the building models using the Linear Static analysis method. However, an RC structure is gradually loaded due to stage-wise construction of the walls, floors, and structural components. Upon construction completion, the live load is applied in the form of occupancy. Using the Construction Sequence Analysis (CSA) method, all loads are applied according to the construction order, and application timing corresponds to actual construction.

According to Chakrabarti et al. (1978)[3] and Chang-Koon Choi et al. (1992)[4], the CSA approach reports responses that are different from the typical Linear Static Analysis (LSA) method, which is a one-step analysis method. Due to the time-dependent characteristics of concrete, Kwak & Kim (2006)[14] proposed a construction sequence method for analysis for designing RC buildings. Dinar et al. (2014) [10] and Correia & Lobo (2017)[5] investigated the effect of sequential self-weight on construction. Ha et al. (2017)[12] recommended considering the time-dependent effect of the concrete during the design stage of tall buildings and created an algorithm for the construction stage to evaluate the

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results with a laser survey. Afshari et al. (2017)[1] suggested an improved correction factor approach. When employing the CSA approach, Secer & Arslan (2018) [16] and Zucca et al. (2018) [17] both discovered a sizable change in vertical column displacements. Elansary et al. (2021) [11] found that one-step analysis results in an unsafe solution in some element zones and an uneconomic solution in others. Since creep and shrinkage are ongoing processes, the CSA method will yield different results at various points in the analysis. Most of these investigators omitted the role of time and primarily assessed responses during live load application. Nehal et al. [6] have concluded that "98% to 99% of the total 50th-year axial shortening, and beam moments respectively are observed on completion of 30 years from the time of live load application. Therefore, it is advised to analyse using the CSA method up to a minimum time of 30 years after the application of the live load, taking the effects of creep and shrinkage into account, rather than up to 50 years, as the procedure is time-consuming and laborious." In this study, all models were analysed up to 30 years after the application of live load, considering the effects of creep and shrinkage.

Vishal et al. (2000) [19] analysed G+19 floors, while Dubey & Bhadauria (2017) [11] analysed 50-floor RC buildings but studied only axial shortening for comparison with the conventional one-step method. Most investigators concentrated the study on axial shortening and differential shortening of vertical members. They overlooked the study of the effect of this axial shortening on the bending moment of beams. Thus, to fill this gap, additional research is required to study and compare the changes that occur in beam moments by CSA and LSA methods. Hence, the stakeholders of the construction industry would realise the significance of the CSA method and understand the importance of adopting it. The study calculates the sensitivity of beams by comparing the bending moment at different sections of beams induced in the CSA the LSA method at every floor level of building models. Beams were divided into different categories based on their sensitivity Index (SI). Four RC moment framed building models with and without RC shear walls of the same plan area, but different spans were selected to evaluate the effect of various beam spans. The building models were analysed using Midas Gen 17[15]. The code of practice of the Indian Roads Congress -IRC: 112-2011[13] was used to consider the long-term effects of concrete-like creep and shrinkage in CSA. This study's analysis and design are undertaken as per the Indian standard code of practice.

2. Materials and Methods

2.1. Building Models

Four 40-storied RC framed building models of symmetrical plans with varying plan grids, as shown in Table 1 and Fig. 1(a)-1(d), were selected for this study. The floor height of the models was 3.2m. Models were analysed and designed using the Indian Standard Code of Practice, with a live load of 2 kN/m^2, floor finishing load of 1 kN/m^2, and brick wall load of 6.5 kN/m by the LSA method.

Table 1. Details of building models

Models	Plan size, mxm	Beam grid, m x m	Total storey numbers	Specific details
Plan A	40 X 40	8 X 8	40	With Central Shear Wall
Plan B	40 X 40	5.72 X 5.72	40	With Central Shear Wall
Plan C	40 X 40	4.44 X 4.44	40	With Central Shear Wall
Plan A0	25 X 25	5 x 5	40	Without Shear wall

The designed cross-sections of structural members for all building models are shown in Table 3. Properties of the grade of concrete and steel used for modelling buildings are specified in Table 2.

Table 2. Properties of materials

Material properties	Reinforcement grade -Fe 415	Concrete grade -M 25
Yield Stress	415 N/mm2	-
Compressive strength after 28 days of curing	-	25 N/mm2
Modulus of Elasticity	2X105 N/mm2	2.5X104 N/mm2
Weight per unit volume	76.973 kN/m3	23.6 kN/m3
Poisson's Ratio	-	0.2

Table 3. Cross-sections of members

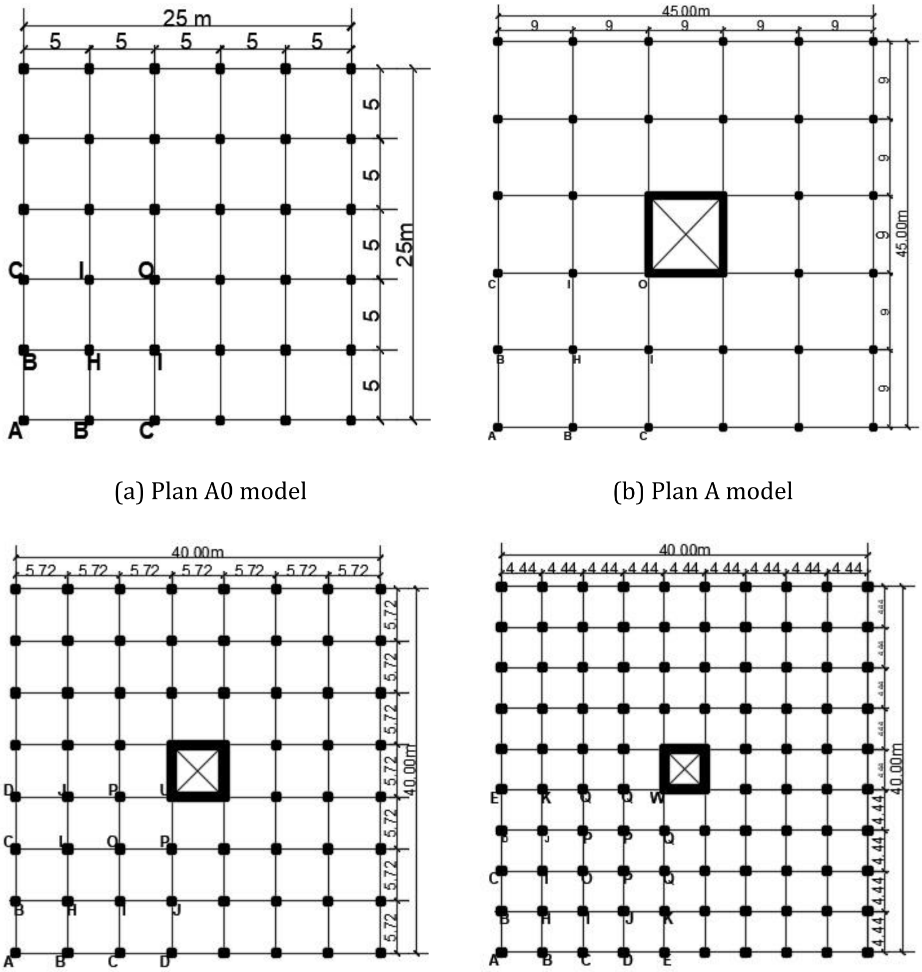
Floor No.	Column size, m x m				Shear wall size, mm		
	Plan A	Plan B	Plan C	Plan A0	Plan A	Plan B	Plan C
1st to 5th	1.6 x1.6	1.3x1.3	1.1x1.1	1.6 x1.6	550	500	500
6th to 10th	1.4x1.4	1.2x1.2	1.0x1.0	1.4x1.4	550	500	500
11th to 15th	1.3x1.3	1.1x1.1	0.9x0.9	1.3x1.3	450	400	400
16th to 20th	1.2x1.2	1.0x1.0	0.8x0.8	1.2x1.2	450	400	400
26th to 30th	1.0x1.0	0.8x0.8	0.6x0.6	1.1x1.1	350	300	300
31st to 35th	0.9x0.9	0.7x0.7	0.5x0.5	1.0x1.0	250	200	200
36th to 40th	0.7x0.7	0.6x0.6	0.4x0.4	0.9x0.9	250	200	200
Beam Size	0.35x0.75	0.3x0.6	0.3x0.5	0.7x0.7	-	-	-

All models with the same design cross-section were analysed by the CSA method. Stage-wise construction loads were applied to all RC building models considering a construction cycle of seven days. The formwork was undertaken to cast the first slab, and the first slab concreting was done on the third day of construction. As shown in Table 4, different loads were applied at different stages following the actual on-site construction sequence and its timing.

As per the time period study of Nehal et al. [6], all models were analysed up to a minimum time of 30 years after the application of the live load, considering the effects of creep and shrinkage.

2.2. Material Properties Related to Creep & Shrinkage

To calculate the long-term shortening due to creep and shrinkage in the CSA method, basic equations for creep co-efficient and the drying shrinkage strain given in IRC: 112-2011[12] (ANNEXURE A-2, page no.237 to 240) code were used.



(a) Plan A0 model

(b) Plan A model

(c) Plan B model

(d) Plan C model

Fig. 1 Plan of different building models

Factors considered while calculating the co-efficient of creep include relative humidity, concrete age at loading, cross-sectional area, concrete strength, notional size of the member in mm, the perimeter of the member in contact with the atmosphere, age of concrete in days at the time considered, cement type, and the temperature adjusted age of concrete at loading in days. Similarly, the parameters considered for calculating the shrinkage strain are mean compressive strength, type of cement, and relative humidity.

As per the equations given in IRC: 112-2011[12], MIDAS Gen-17 calculates the long-term shortening due to creep and shrinkage in the CSA method based on above mentioned parameters.

2.3. Sequential Loads on Building Models

Stage-wise construction loads were applied on all RC building models and analysed by the CSA method for a construction cycle of seven days. The formwork was undertaken for the first slab casting and concreting of the first slab was done on the third day of construction.

As shown in Table 4, different loads were applied at different stages following the actual onsite construction sequence and its timing. These stage-wise loading sequences and timing for all stages were activated considering long-term properties of concrete like creep and shrinkage. The analysis was undertaken for 30 years for the RC building models.

Table 4. Stage-wise sequential loading for the CSA method

Sr. No	Type of load	Starting floor	The load cycle begins at/with	Cycle time
1	Self-weight of RC members	the first floor	On the first day of first stage one, i.e., on 22nd day, when the age of first-floor slab is19 days	7 days
2	Load of the brick wall	the first floor	On the first day of fifth stage, i.e., on the 29th day	7 days
3	Load of floor finishing	the first floor	On the first day of sixth stage, i.e., on the 36th day	7 days
4	Live load	on all floors	At the last stage i.e., after allowing 90 days for occupancy after completion of construction work including finishing work.	Single time

3. Results and Discussion

In this study, the self-weight of structural members, a load of a brick wall, a load of floor finishing, and a live load were applied stage-wise as per construction sequence and scheduled timing, in line with the actual construction, as explained in Table 4. This changes the structural responses in the CSA method. Since the analysis was undertaken for 30 years from the application of live load, the time-dependent properties of concrete, like creep and shrinkage, also change the bending moment of beams in the CSA analysis method.

3.1. Sensitivity Analysis

The bending moments induced in LSA and CSA methods at left-end support, mid-span, and right-end support for all beams of all four building models were compared. To measure the level of sensitivity of moments, the dimensionless coefficient Sensitivity Index- 'SI' was introduced.

$$Sensitivity\ Index\ (\ SI\ ) = \frac{\text{Bending Moment induced in CSA method}}{\text{Bending Moment induced in LSA method}}$$

SI coefficient for all beams on every floor for all plans were calculated, tabulated, and plotted in a graph.

3.2. Sensitivity Categories for Left End Moments

Graph of Sensitivity Index v/s Storey numbers, for left-end Moment, for a beam 'AB' of Plan C was plotted in Fig. 2.

It was observed that SI at the left end of beam 'AB' increases from 0.772 to 1.006 as moving from the top (40th) storey to the 8th storey. After that, SI again reduces to 0.972 from the 7th to the 1st storey. As storey numbers increase, the left-end moment sensitivity increases from the 8th floor. The LSA method provides a 0.6% lesser to 22.76 % higher bending moment than the CSA method when moving from the bottom to the top storey (at the left end). The higher storeys were more vulnerable in comparison to the lower storeys.

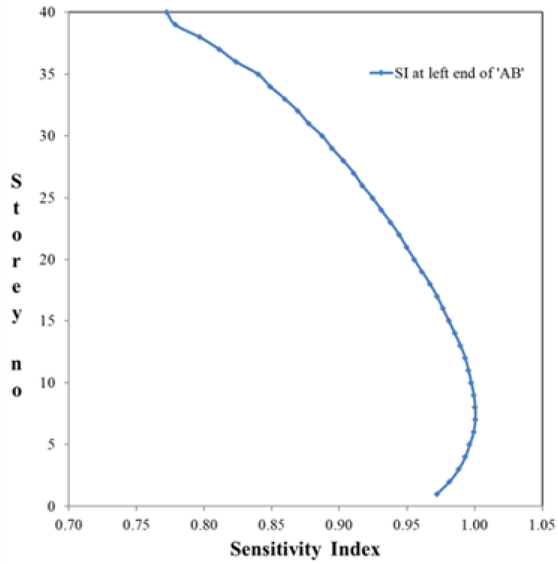


Fig. 2 Sensitivity Graph of beam 'AB' of Plan C

The SI at the left end of beam 'O1P1' increases from 0.964 to 1.345 while moving from 1st floor to 40th floor as shown in Fig. 3. From 1st to 10th storey, LSA provides 3.57% higher moments than CSA. From the 10th to the 34th storey LSA provides 31.3% lesser moments than CSA. On the 34th and 39th floor, 'SI' suddenly increases to 1.313 & 1.346, respectively, i.e. LSA provides 31.3% to 34.6% lower bending moments than CSA.

Similarly, as per Fig. 3, in Beam 'BC', 'SI' reduces from 0.964 to 0.848 while moving from the 1st floor to the 40th floor, i.e. LSA provides 3.57% to 15.2% higher values than CSA. However, sensitivity in Beam 'DE'& 'EF' 'SI' varies in a range of 0.959 to 0.961 for all storeys, i.e. LSA provides 4.1% to 3.9% higher moments than LSA. The deviation of a moment in CSA from LSA is comparatively lesser here as storey numbers increase.

From the 'Sensitivity index of left end moment V/S floor number' for beams of all building models as shown in Fig. 3, Fig. 4(a)-4(c) and Fig. 5, the following observations were made:

- Sensitivity index V/S floor number graph of left end moment of beams 'AB', 'GH', and 'MN' of Plan A model show a similar pattern and range of sensitivity Index.
- Similarly, the sensitivity index graph of the left end moment of beams 'AB', 'GH', 'MN' and 'RS' of the Plan B model, beams 'AB', 'GH', 'MN', M1N1'and 'TS' of Plan C model and beams 'AB', 'GH' and 'MN' of Plan A0 model also show a similar pattern and range of Sensitivity index.

All these beams were grouped into one category, which is CAT-III.

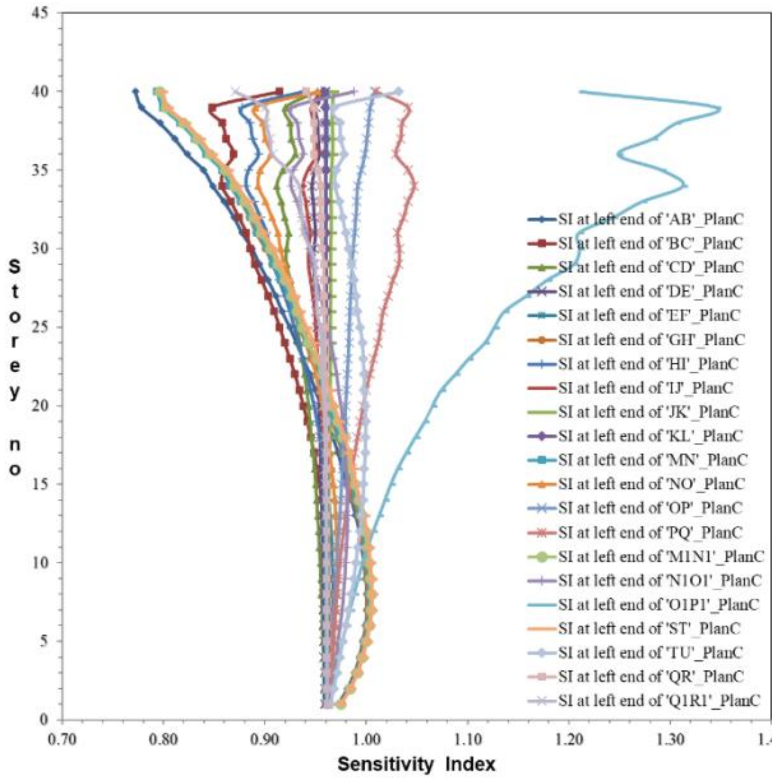
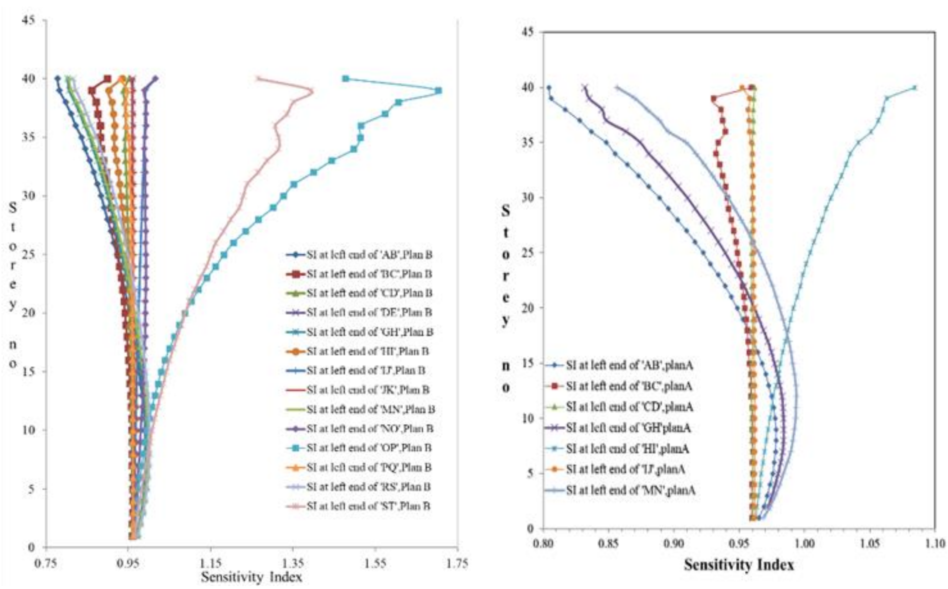
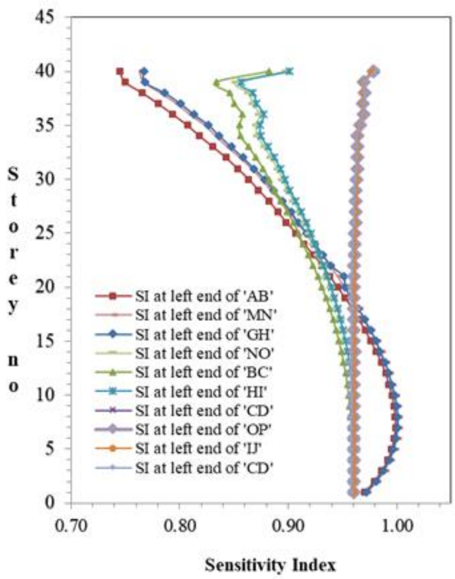


Fig. 3 Sensitivity Graph at Left end for all beams, Plan C



(a) Plan B model

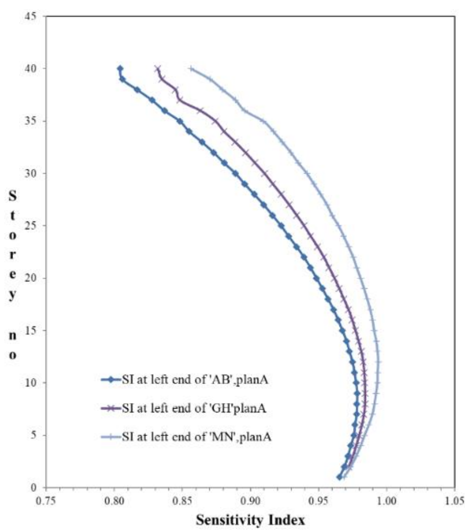
(b) Plan A model



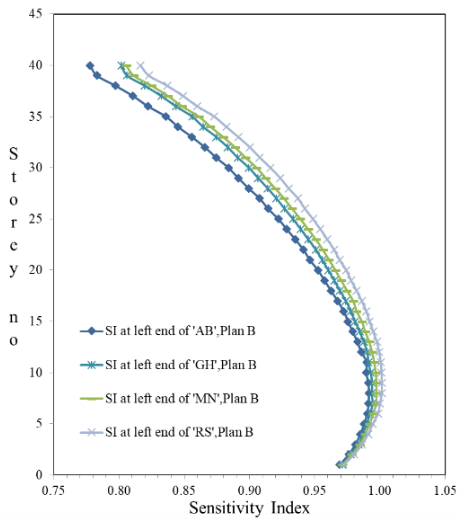
(c) Plan A0 model

Fig. 4 Sensitivity Graph at Left end for building models

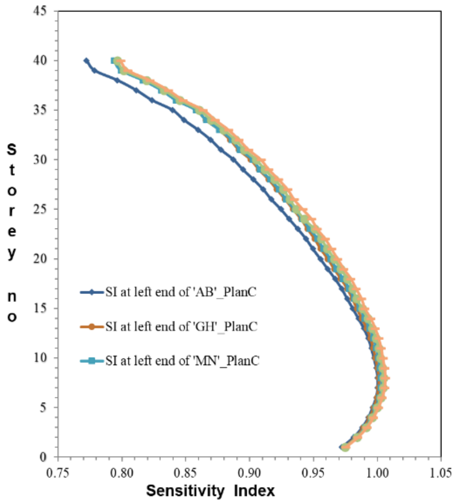
A different set of graphs with a similar pattern and range of SI were identified from the left-end support moments in beams of all models, as shown inFig.3 and Fig.4. Finally, all beams were divided into five different categories. Beams of CAT I, CAT II, CAT III, CAT IV and CAT-V with their Sensitivity range are shown in Fig. 5-9 and tabulated in Table 5. the following observations were made:



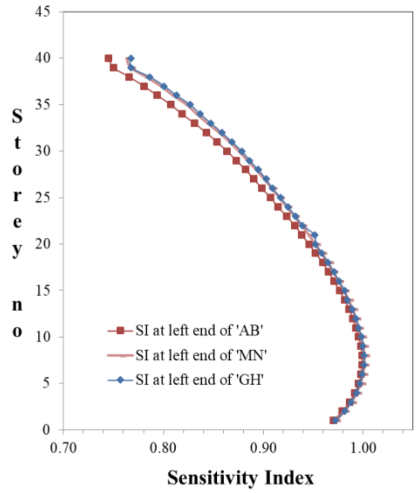
(a) Plan A model



(b) Plan B model



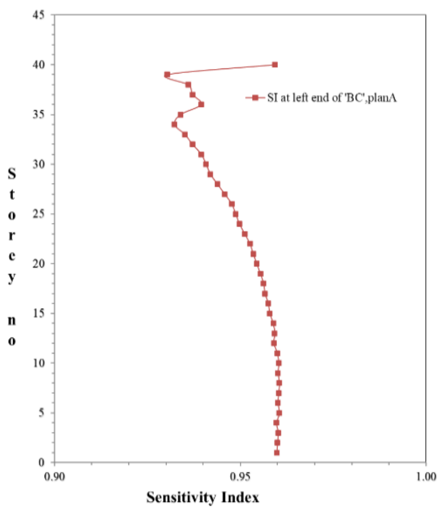
(c) Plan C model



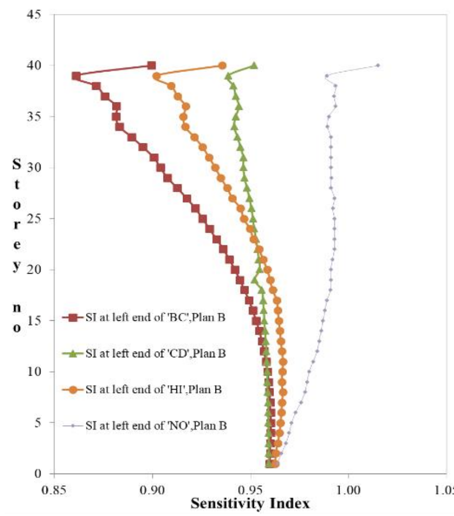
(d) Plan A0 model

Fig. 5 Sensitivity graph at left-end support for beams of CAT III

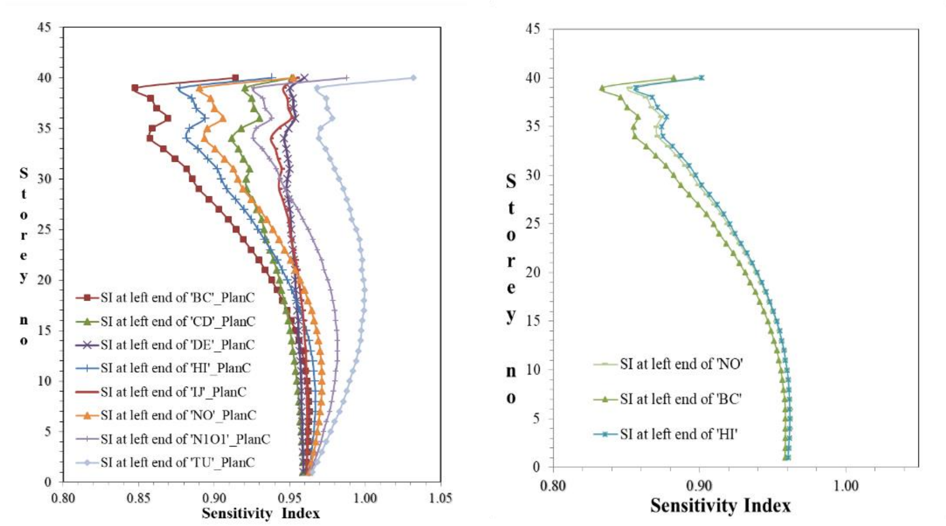
- As shown in Fig. 5, in Cat-III, the value of SI increases up to the 7th and 8th floors. Later it reduces up to the top floor in all building models. As shown in Fig. 6 to 8, in CAT-II, CAT-IV and CAT-V, the sensitivity of the bending moment increases as the building floors increase for all categories of building models. While in CAT-I beams, as shown in Fig. 9, the SI shows highly vulnerable values.
- In Category-III beams, as shown in Fig. 5, the SI varies from 0.8042 to 0.994 in Plan A, 0.78 to 1.0014 in Plan B, 0.7724 to 1.006 in Plan C and 0.745 to 1.00 in Plan A0. Thus, LSA provides 19.58% to 0.61% higher, 22% higher to 0.14 % lower, 22.76% higher to 0.6% lower and 25.5% higher left end bending moment in Plan A, Plan B, Plan C and Plan A0, respectively.



(a) Plan A model



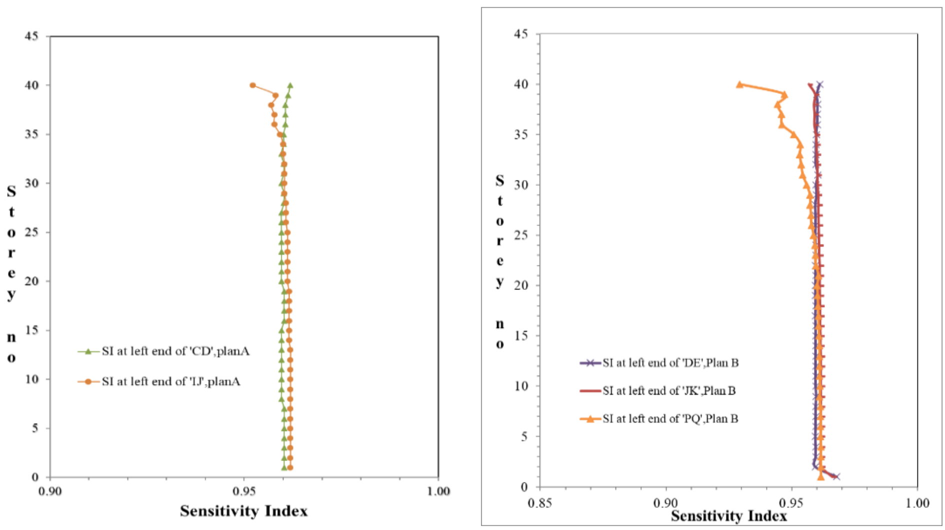
(b) Plan B model



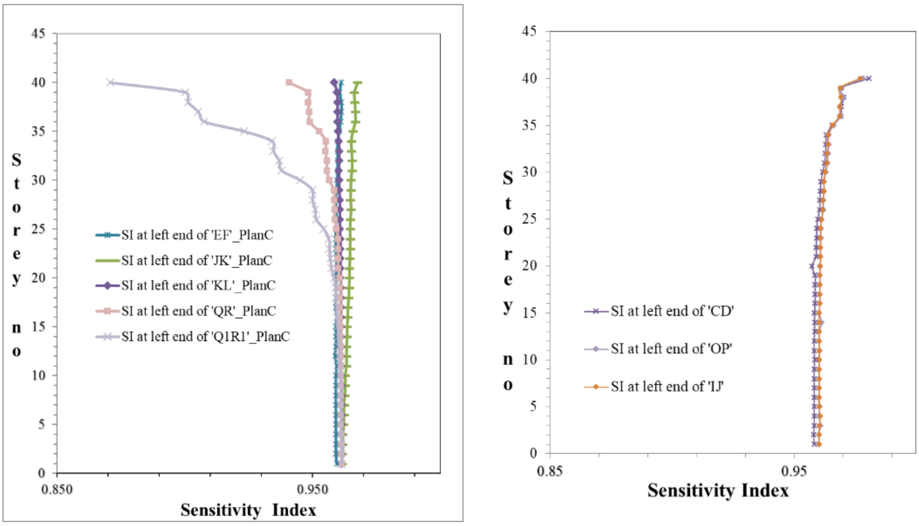
(c) Plan C model (d) Plan A0 model

Fig. 6 Sensitivity graph at left-end support for beams of CAT IV

- In Category-IV beams, as shown in Fig. 6, the SI varies from 0.930 to 0.9605 in Plan A, 0.8609 to 1.0165 in Plan B, 0.8478 to1.0320 in Plan C, and 0.830 to 0.977 in Plan A0. Thus, LSA provides 7% to 3.95% higher, 13.91% higher to 1.65% lower, 15.22% higher to 3.2% lower and 17% to 2.3% higher left-end bending moment in Plan A, Plan B, Plan C, and Plan A0, respectively.



(a) Plan A model (b) Plan B model

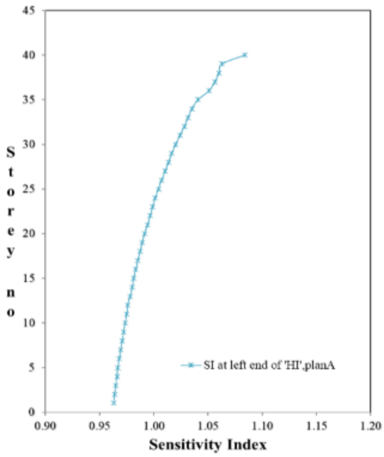


(c) Plan C model (d) Plan A0 model

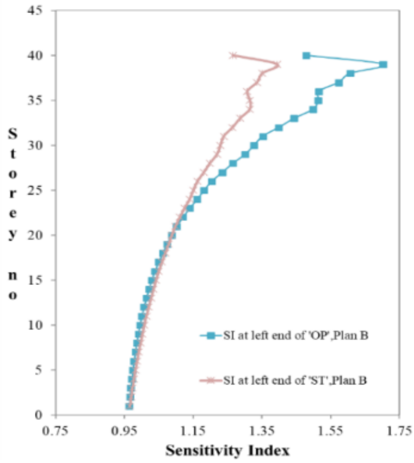
Fig. 7 Sensitivity graph at left-end support for beams of CAT V

- In Category-V beams, as shown in Fig. 7, the SI varies from 0.9522 to 0.9619 in Plan A, 0.9222 to 0.9679 in Plan B, 0.8709 to 0.9676 in Plan C and 0.957 to 0.981 in Plan A0. Thus, LSA provides 4.78% to 3.81% higher, 7.78% to 3.21% higher, 12.91% to 3.24% higher and 4.3% to 1.9% higher left-end bending moment in Plan A, Plan B, Plan C, and Plan A0 respectively.
- In Category-II beams, as shown in Fig. 8, the SI varies from 0.963 to 1.084 in Plan A, 0.9640 to 1.7024 in Plan B and 0.9643 to 1.3452 in Plan C. Thus, LSA provides 3.7% higher to 8.4% lower, 2.6% higher to 70.24% lower, and 3.6% higher to 34.52% lower left end bending moment in Plan A, Plan B, and Plan C, respectively.
- In Category-I beams, as shown in Fig. 9, the SI varies from 3.48 to -11.087 in Plan A, -1.0937 to 4.8316 in Plan B and -10.209 to 36.9457 in Plan C. Thus, LSA provides 248% to 108% lower, 209.34% to 383.16% lower, and 110.209% to 3594.57% lower left end bending moment in Plan A, Plan B, and Plan C, respectively. CAT-I beams surrounding the RC shear walls were the most vulnerable and sensitive category among all categories.
- As the span increases, the sensitivity index decreases, i.e. the difference between the left end moment by the CSA method and LSA method in all categories of beams.
- In Plan A0, only three categories, CAT-III, CAT-IV and CAT-V, were observed. CAT-I and CAT-II, which were highly vulnerable, seem absent here. Hence RC shear walls increase sensitivity.
- The study of all the beams suggests that LSA provides 3.6% higher to 70.24% lower, 25% higher to 0.14% lower, 17% to 3.2% lower, and 12.91% to 1.9% higher left-end support bending moments in CAT-II, CAT-III, CAT-IV and CA-V, respectively.
- While left-end support moments of CAT-I behave very irregularly, the LSA provides 110% to 3594.57% lower right-end support bending moments.
- Hence, sensitivity varies from CAT-I to Cat-V in descending order while progressing from CAT-I to CAT-V in the case of left-end support moments. The most sensitive category is CAT-I.

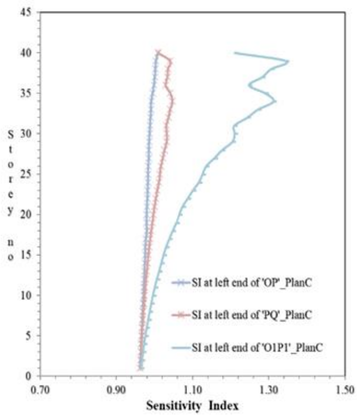
- Sensitivity of the left-end moment increases as storeys increase in all categories except CAT-I. In CAT-I beams of Plan A and Plan B models, the maximum variation in SI is at intermediate floors. Maximum variation in SI is at higher floors in CAT-I beams of the Plan C model.



(a) Plan A model

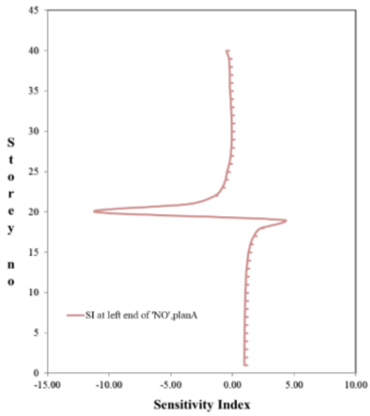


(b) Plan B model

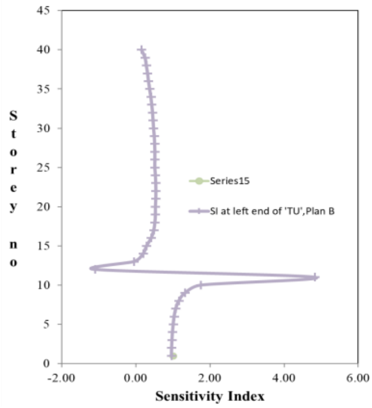


(c) Plan C model

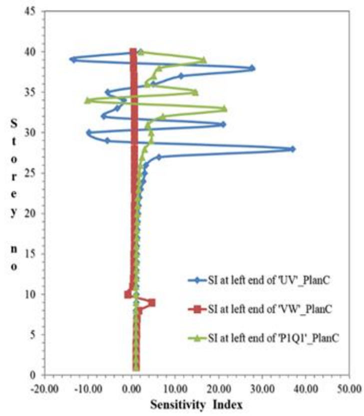
Fig .8 Sensitivity graph at left-end support for beams of CAT II



(a) Plan A model



(b) Plan B model



(c) Plan C model

Fig. 9 Sensitivity graph at left-end support for beams of CAT I

Beams are presented with colour codes, as per their categories as shown in Fig. 10

3.3. Sensitivity Categories for Right-End Support Moments

A similar pattern of SI graphs was observed in the 'sensitivity index of the right end moment V/S storey number for beams in all plans. All beams were divided into the same five categories, CAT I, CAT II, CAT III, CAT IV and CAT V. Beams of all plans as per their categories and sensitivity range are tabulated in Table 6. Fig. 11 shows a graph of 'SI V/s storey number' for CAT III, which was found critical for right-end support moments. Observations are listed below:

- The maximum to minimum SI range of right-end beam moments varies from 0.588 to 1.155, 0.8299 to 1.105, 00.89 to 62.97to -105.82, 0.8858 to 2.1149 and 0.8755 to 0.97966 in CAT-I, CAT-II, CAT-III, CAT-IV and CAT-V, respectively.
- LSA provides 42.29 % higher to 15.5% lower, 17.01% higher to 10.5% lower, 11.75% higher to 111.49% lower and 2.034% to 12.45% higher right-end support bending moments in CAT-I, CAT-II, CAT-IV and CAT-V, respectively.

Table 5. Range of Sensitivity Index of left end moments for all Categories

Categories of beams		Range of left end moment SI for various categories of beams of various plans				
		Plan A	Plan B	Plan C	Plan A0	SI-Range amongst all models
CAT-I	Beams	NO	TU	UV, P1Q1,VW	NA	LSA gives 110.21 % to 3594.57% lower
	SI-range	3.48 to -11.087 LSA gives 248%lower To 1087% lower BM	-1.0937 to 4.8316 LSA gives 209.34% lower to 383.16% lower BM	-10.209 to 36.9457 LSA gives 110.209% Lower to 3594.57% lower BM		
CAT-II	Beams	HI	OP, ST	O1P1, PQ, OP	NA	LSA gives 3.6%higher To 70.24% lower BM
	SI-range	0.963 to 1.084 LSA gives 3.7% higher to 8.4% lower BM	0.9640 to 1.7024 LSA gives 3.6% higher to 70.24% lower BM	0.9643 to 1.3452 LSA gives 3.6%higher to 34.52% lower BM		
CAT -III	Beams	AB, GH, MN	AB, GH, MN, RS	AB, GH, MN, M1N1, ST	AB,GH,MN	LSA gives 25% higher to 0.14% lower BM
	SI-range	0.8042 to 0.994 LSA gives 19.58% to 0.61% higher BM	0.78 to 1.0014 LSA gives 22% Higher to 0.14% lower BM	0.7724 to 1.006 LSA gives 22.76% higher to 0.6% lower BM	0.745 to 1.00 LSA gives 0 to 25.5% higher BM	
CAT -IV	Beams	BC	BC, HI, CD, NO, IJ	BC, HI, NO, CD,N1O1,IJ, DE, UT	BC,HI, NO	LSA gives 17% to 3.2% lower BM
	SI-range	0.930 to 0.9605 LSA gives 7% to 3.95% higher BM	0.8609 to 1.0165 LSA gives 13.91% higher to 1.65% lower BM	0.8478 to1.0320 LSA gives 15.22% to 3.2% lower BM	0.830 to 0.977 LSA gives 17% to 2.3% higher BM	
CAT -V	Beams	CD,IJ	PQ, JK,DE	JK,EF,KL, QR,Q1R1	CD,OP,IJ	LSA gives 12.91% to 1.9% higher BM
	SI-range	0.9522 to 0.9619 LSA gives 4.78% to 3.81% higher BM	0.9222 to 0.9679 LSA gives 7.78% to 3.21% higher BM	0.8709 to 0.9676 LSA gives 12.91% to 3.24% higher BM	0.957 to 0.981 LSA gives 4.3% to 1.9% higher BM	

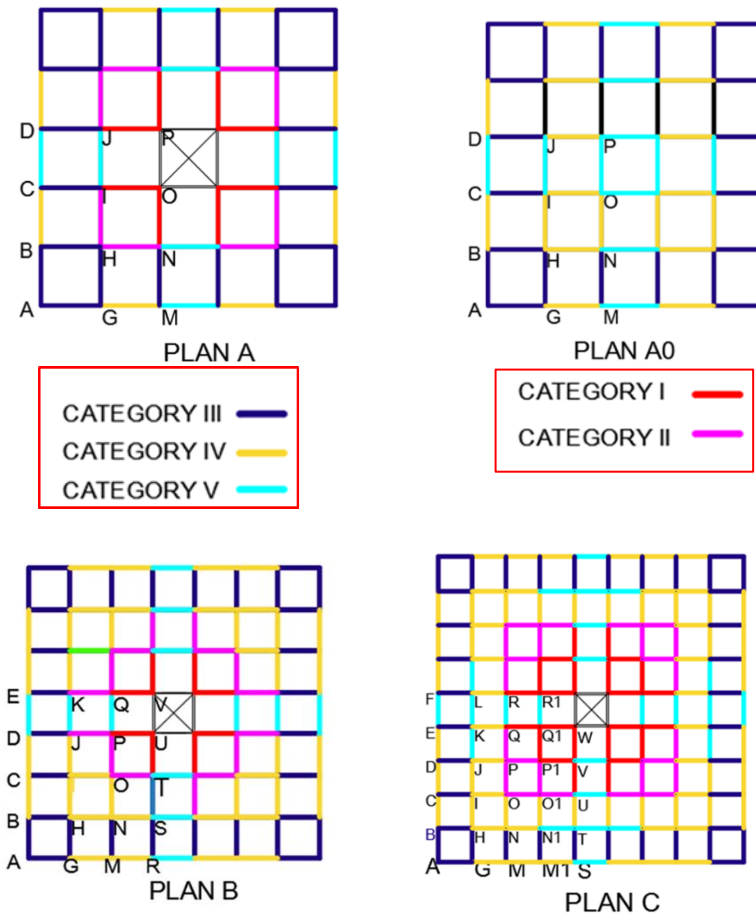
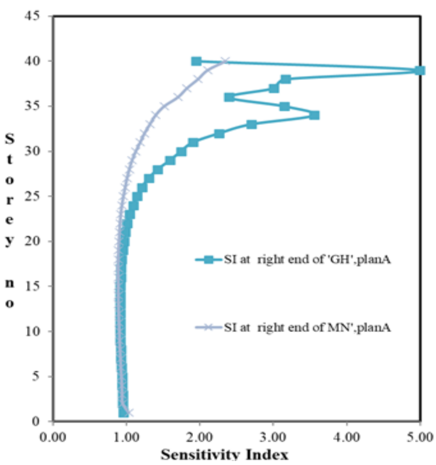


Fig. 10 Different categories of beams of Plan A, Plan B, Plan C and Plan A0 models

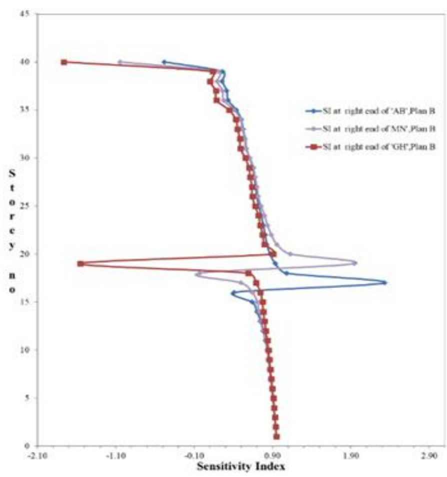
- While right-end support moments of CAT-III behave very irregularly. LSA provides 19.5775% higher to 6197 % lower right-end support moments. Hence sensitivity varies in descending order from CAT-V, CAT-II, CAT-I, and CAT-IV for right-end support moments. The most sensitive category is CAT-III.
- Sensitivity of the right-end moment increases as storeys increase in all categories except CAT-III. In CAT-III beams of Plan B, Plan C and Plan A0 models, the maximum variation in SI is at intermediate floors, while in the Plan A model, it is at higher floors.

A similar pattern of graphs with a similar range of SI was observed in the ‘sensitivity index of mid-span moment V/S floor number’ for beams in all plans. All beams were divided into the same four categories, CAT I, CAT II, CAT III and CAT IV. Beams of all plans as per their categories and range of sensitivity are tabulated in Table 7. While Fig. 12 shows a graph of ‘SI v/s storey number’ for CAT III, which was found very critical for mid-span moments. Observations are listed below:

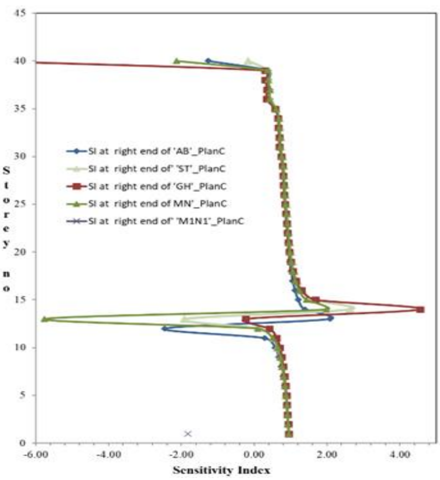
- The range of maximum to minimum SI of right-end beam moments varies from 0.3723 to1.1435, 0.9047 to 1.0761, 0.2820 to 1.1016, 0.830 to 1.0745 and 0.957 to 1.4442 in CAT-I, CAT-II, CAT-III, CAT-IV and CAT-V, respectively.
- The LSA provides 9.53% higher to 7.58% lower, 17% higher to 7.45% lower and 4.3% higher to 44% lower mid-span bending moments in CAT-II, CAT-IV and CAT-V, respectively.
- While the range of mid-span moments of CAT-I and CAT-III was large, the LSA provides 62.77% higher to 14.35% lower and 71.8% higher to 10.16% lower mid-span moments in CAT-I and CAT-III beams, respectively. Hence the sensitivity of CAT-III was larger than CAT-I, CAT-IV, CAT-IV and CAT-II in descending order in the case of mid-span moments. The most sensitive categories were CAT-III and CAT-I, with CAT-I being the most sensitive.
- The sensitivity of the mid-span moment increases as storeys increase in all categories. However, significant variation was observed in the top 10 to 15% of the floors. In CAT-III beams, the SI remains constant up to 60% to 62.5%, 37.5% to 40%, 30% to 32.5% and 27.5% of floors in Plan A, Plan B, Plan C and Plan A0 models. The SI suddenly increases at a significantly higher range up to the top floor. The number of storeys up to which the SI graph remains constant also increases the span increases.
- In CAT-I beams, the SI remains constant up to 47.5%, 27.5% and 22.5% of floors in Plan A, Plan B and Plan C models. Later SI suddenly increases at a significantly high range up to the top floor. The number of storeys up to which the SI graph remains constant increases as the span increases.
- In this category of mid-span moments, as the span decreases, the sensitivity of beam moments increases in all categories of beams.



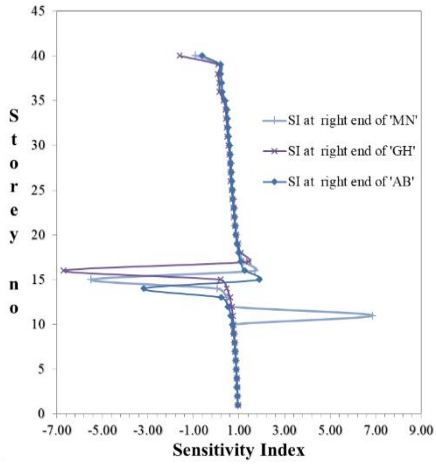
(a) Plan A model



(b) Plan B model

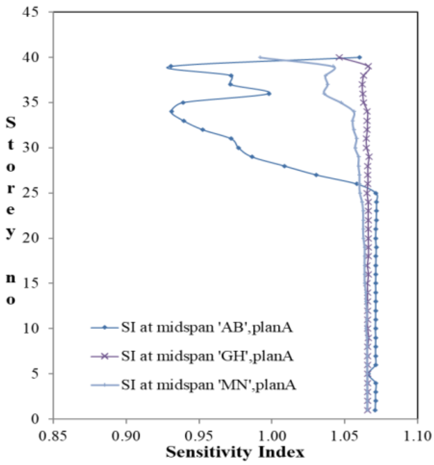


(c) Plan C model

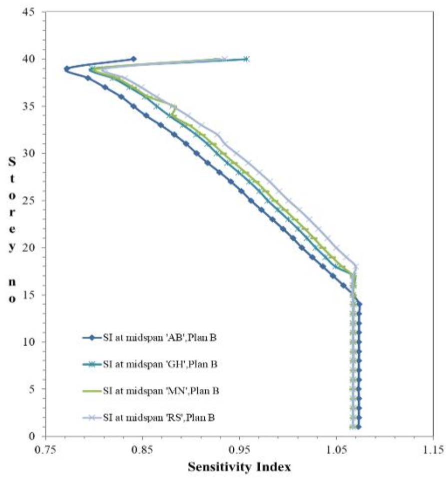


(d) Plan A0 model

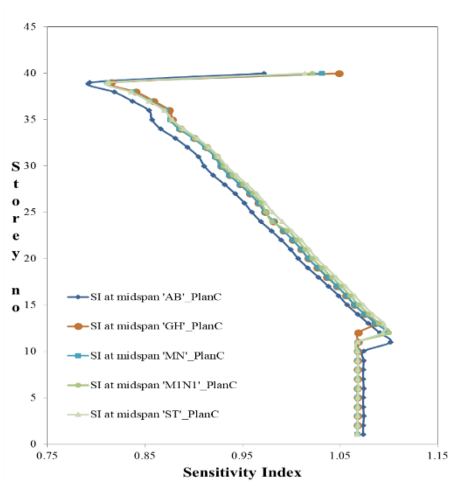
Fig. 11 Sensitivity graph at right-end support for beams of CAT III



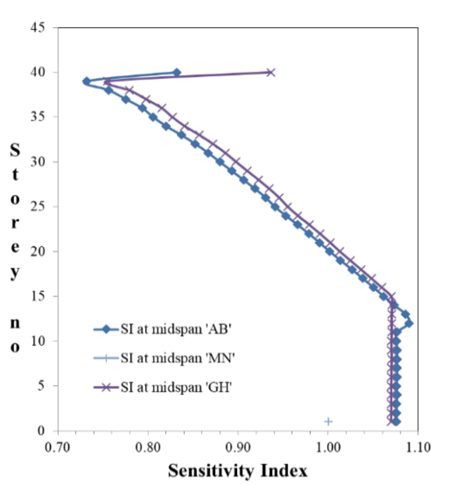
(a) Plan A model



(b) Plan B model



(c) Plan C model



(d) Plan A0 model

Fig. 12 Sensitivity graph at mid-span for beams of CAT III

Table 6. Range of Sensitivity Index of Right End Moments for all Categories

Categories of beams		Range of right-end moment SI for various categories of beams of various plans: Plan A	Plan B	Plan C	Plan A0	SI-Range amongst all models
CAT- I	Beams	NO	TU	UV,P1Q1.VW	NA	LSA gives 42.29 % higher to 15.5% lower BM
	SI-range	0.67 to 0.96 LSA gives 33% to 4% higher BM	0.961 to 0.577 LSA gives 3.925 % to 42.29% higher BM	0.588 to1.155 LSA gives 41.2% higher to 15.5 % lower BM		
CAT-II	Beams	HI	OP,ST	O1P1,PQ,OP	NA	LSA gives 17.01% higher to 10.5% lower
	SI-range	0.89 to 0.96 LSA gives 11% higher to 4% higher BM	0.955to 1.105 LSA gives 4.473% higher to 10.5% lower BM	0.8299 to 0.974 LSA gives 17.01% higher to 2.58% higher BM		
CAT -III Irregular	Beams	AB,GH, MN	AB,GH,MN,RS	AB,GH,MN, M1N1,ST	AB,GH, MN	LSA gives 19.5775% higher to 6197 % lower
	SI-range	0.89 to 62.97 to -105.82	-0.47912 to 3.559 to -15.5379	4.5484 to -7.397	1.887 to 6.868 to -3.188	

		LSA gives 19.577% Higher to 6197% lower to BM	LSA gives 147.92%/ 1653.79% lower to 255.88% lower BM	LSA gives 354.84%lower to 839.72% lower BM	LSA gives 88.7 % lower to 586.8 % to 218.8% lower BM	
CAT -IV	Beams	BC	BC,HI,CD, NO,IJ	BC,HI,NO, CD,N1O1, IJ,DE, TU	BC,HI, NO	LSA gives 11.75% higher to 111.49 lower % BM
	SI-range	1.01 to 0.96 LSA gives 4%higher to 1% lower BM	0.9585 to 1.28397 LSA gives 7.15% higher to 28.397 % lower BM	0.8858 to 2.1149 LSA gives 11.75% higher to111.49% lower BM	0.939 to 1.44 LSA gives 6.1 % higher to 44% lower BM	
CAT -V	Beams	CD,IJ	PQ, JK,DE	QR, Q1R1	CD, OP, IJ	LSA gives2.034% higher to 12.45% higher BM
	SI-range	0.95 to 0.96 LSA gives 5% to 4% higher BM	0.92924 to 0.97966 LSA gives 7.076% to 2.034% higher BM	0.8755 to 0.9676 LSA gives 12.45% higher to 3.24% higher BM	0.958 to 0.981 LSA gives 4.2 % higher to 1.9% higher BM	

Table 7. Range of Sensitivity Index of Mid-Span Moments for all Categories

Categories of beams		Range of mid-span moment SI for various categories of beams of various plans				
		Plan A	Plan B	Plan C	Plan A0	SI-Range amongst all models
CAT- I	Beams	NO	TU	UV,P1Q1, VW	NA	LSA gives 62.77%higher to 14.35% lower BM
	SI-range	0.672265 to 1.064252 LSA gives 32.77% higher to 6.4252% lower BM	0.4189 to 1.0688 LSA gives 58.11% higher to 6.88% lower BM	0.3723 to 1.1435 LSA gives 62.77% higher to 14.35 % lower BM		
CAT-II	Beams	HI	OP,ST	O1P1,PQ,OP	NA	

	SI-range	1.042581 to 1.066484 LSA gives 6.6484 % lower to 4.2581% lower BM	0.9047 to 1.0758 LSA gives 9.53% higher to 7.58% lower BM	0.9446 to 1.0761 LSA gives 5.54 % higher to - 7.61 % lower BM		LSA gives 9.53 % higher to 7.58% lower BM
CAT -III	Beams	AB,GH, MN	AB,GH, MN,RS	AB,GH,MN, M1N1,ST	AB,GH MN,	
	SI-range	0.930755 to 1.0718 LSA gives 6.9245% higher to 7.18637% higher BM	0.7718 to 1.0734 LSA gives 22.82% higher to 7.34% lower BM	0.2820 to 1.1016 LSA gives 71.8% higher to 10.16% lower BM	0.745 to 1.00 LSA gives 0 to 25.5% higher to BM	LSA gives 71.8% higher to 10.16% lower BM
CAT -IV	Beams	BC	BC,HI,CD, NO,IJ	BC,HI,NO, CD,N1O1, IJ, DE, TU	BC,HI, NO	
	SI-range	1.040438 to 1.0718736 LSA gives 4.044%lesser to7.18736% higher BM	0.9949 to 1.0736 LSA gives 0.51% higher to 7.36% lower BM	0.9737 to1.0745 LSA gives 2.63 % higher to 7.45% lower BM	0.830 to 0.977 LSA gives 17% to 2.3% higher BM	LSA gives 17%higher to 7.45% lower BM
CAT -V	Beams	CD,IJ	PQ, JK, DE	JK,EF,KL, QR,Q1R1	CD,OP,IJ	
	SI-range	1.066 to 1.086 LSA gives 6.58% lower to 8.61% lower BM	1.068 to 1.146 LSA gives -6.75% lower to -14.59% lower BM	LSA gives 5.76% lower to 44.42% lower BM	0.957 to 0.981 LSA gives 4.3%To 1.9% higher BM	LSA gives 4.3% higher to 44% lower BM

4. Conclusion

The study concludes:

- Building models of various spans are divided into five different sensitivity categories as per the behavioural patterns of the beams.
- In the case of left end beam moments, CAT-I beams surrounding the RC shear walls are the most vulnerable among all categories. The sensitivity varies from CAT-I to Cat-V in descending order while progressing from CAT-I to CAT-V in case of left-end support moments. The sensitivity of the left-end moment increases as storeys increase in all categories except CAT-I. In CAT-I, the beams of Plan A and Plan B models, the maximum variation in SI is observed at intermediate floors. While in CAT-I beams of the Plan C model, maximum variation in SI is observed at higher floors.
- The sensitivity varies in descending order from CAT-V, CAT-II, CAT-I, and CAT-IV in the case of right-end support moments. The most sensitive category is CAT-III. The sensitivity of the right-end moment increases as storeys increase in all

categories except CAT-III. In CAT-III beams of Plan B, Plan C and Plan A0 models, the maximum variation in SI occurs at intermediate floors. While in CAT-III beams of the Plan A model, the maximum variation in SI is observed at higher floors.

- The sensitivity of CAT-III is larger than CAT-I, CAT-IV, CAT-IV and CAT-II in descending order in the case of mid-span moments. The most sensitive categories are CAT-III and CAT-I, with CAT-I being the most sensitive. The sensitivity of the mid-span moment increases as storeys increase in all categories. However, significant variation is observed in the top 10% to 15% of floors in CAT-I. In CAT-III beams, the SI remains constant up to 60% to 27.5% of the total storey in various plan models, and in CAT-I beams, the SI remains constant up to 47.5% to 22.5% of the total storey in various plan models. Later the SI suddenly increases at a significantly high range up to the top floor. As the span increases, the number of storeys up to which the SI graph remains constant also increases.
- After studying all the beams, it is observed that LSA provides 3.6% higher to 70.24% lower left-end support bending moments in CAT-II, CAT-III, CAT-IV and CAT-V, respectively. While left-end support moments of CAT-I behave very irregularly, the most sensitive category is CAT-I in the case of left-end support moments.
- LSA provides 42.29% higher to 111.49% lower right-end support bending moments in CAT-I, CAT-II, CAT-IV and CAT-V. In contrast, right-end support moments of CAT-III behave very irregularly. Hence the most sensitive category is CAT-III.
- LSA provides 17% higher to 44% lower mid-span bending moments in CAT-II, CAT-IV and CAT-V. At the same time, the range of mid-span moments of CAT-III and CAT-I behave very irregularly.
- In Plan A0 type building models, only three categories, CAT-III, CAT-IV and CAT-V, are observed. CAT-I and CAT-II, which are highly vulnerable, seem absent here. Hence, the RC shear walls increase sensitivity.
- As span decreases, the sensitivity of beam moments increases in all categories of beams.

The study concludes that it is advisable to use the CSA method considering the effects of concrete's time-dependent properties when designing RC moment-frame high-rise buildings.

5. Limitations of the Study

The study is undertaken for symmetrical RC frame high-rise buildings considering a construction cycle of seven days with an occupancy period of 90 days in the CSA method. Analysis and design are undertaken as per the Indian standard code of practice.

Acronym

CSA: Construction Sequence Analysis considering creep and shrinkage.

LSA: Linear Static Analysis Method.

SI: Sensitivity Index.

Plan A, Plan B: RC building model of plan A,plan B , etc.

RC: Reinforced Concrete.

CAT: Category.

BM: Bending Moment

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