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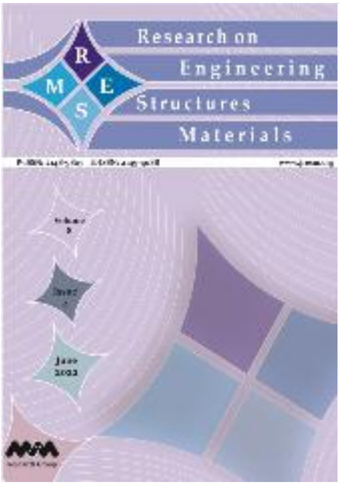

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Online Publication Date: 20 Aug 2022
URL: http://www.jresm.org/archive/resm2022.414st0309.html
DOI: http://dx.doi.org/10.17515/resm2022.414st0309

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Desai NM, Vasanwala S. Influence of time period and derivation of critical storey limit for RC frame buildings using construction sequence method of analysis. *Res. Eng. Struct. Mater.*, 2023; 9(1): 195-208.

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Research Article

Influence of time period and derivation of critical storey limit for RC frame buildings using construction sequence method of analysis

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Article Info

Article history:

Received 09 Mar 2022
Revised 09 Jun 2022
Accepted 15 Aug 2022

Keywords:

Axial shortening;
Construction sequence method of analysis;
Critical time period;
Critical storey limit;
Time-dependent properties of concrete

Abstract

Construction Sequence Analysis (CSA) is a method that follows real-time onsite construction practices like construction sequence, sequential loading, and timing. Properties of concrete, like Creep and shrinkage are time-dependent properties of concrete, so it is crucial to determine the period up to which critical responses are received during a building's life. This study observes the different responses of structural members seeing the long-term effect of concrete properties for up to 50 years, cohesive to the standard lifespan of RC structures in India. The study derives the most critical time during the entire life of the building using the CSA method. According to this study, 98% to 99% of the 50th-year responses are attained within 10950 days after applying live load. The study recommends analysing RC structures for 10950 days using the CSA method instead of ending at the time of live load application or continuing analysis up to 50 years. It is important to know the limit of total storeys above which the behaviour of vertical members becomes vulnerable in RC buildings. The study also determines the critical storey limit of RC moment frame building over which the CSA method must be utilised. Hence, this study uses the CSA and Linear Static Analysis method to analyse 12 RC building models of various beam spans and total storeys. The study concludes that the CSA method should be mandatory for buildings with more than nine stories.

1. Introduction

Structural engineers use the Linear Static method to analyse and design an RC building by simultaneously applying all loads to the building models. An RC structure is gradually loaded as it is built, due to factors including the own weight of structural components, walls, and floor finishing. After construction is finished, occupancy is applied in terms of the live load. All loads are applied in accordance with the order of construction using the Construction Sequence Analysis (CSA) method, and the timing of application matches that of actual construction. Because creep and shrinkage are ongoing processes, the Construction Sequence Analysis (CSAcs) method will yield different results at various points in the analysis. Many researchers have studied CSA method.

Chakrabarti et al. [3] and Chang-Koon Choi et al. [4] argue that the (CSA) method reports responses, which are different from the conventional one-step Linear Static Analysis (LSA) method. Kwak & Kim [10] proposed a construction sequence method that considers deformation in concrete due to its time-dependent properties. A computational method was used by Dinar et al. [6] and Correia & Lobo [5] to investigate the impact of sequencial self-weight on construction. Ha et al. [8] developed an algorithm for the construction stage to assess the outcomes with a laser survey and advised taking into account the time-

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DOI: http://dx.doi.org/10.17515/resm2022.414st0309

dependent effect of the concrete during the design stage of tall buildings. An improved correction factor approach was proposed by Afshari et al. [1]. Both Secer & Arslan [12] and Zucca et al. [13] found a substantial change in vertical column displacements while using CSA method. One-step analysis yields an unsafe solution in some element zones and an uneconomic solution in others, according to Elansary et al. [7].

Most of these investigators omitted the role of time and primarily assessed responses at the time of live load application. However, Casalegno et al. [2] estimated the difference in vertical displacement for a long time in cable-stayed bridges subjected to creep. They did notice increased deflection due to creep for longer periods.

Additional research is required to fully comprehend the impact of time period on the responses of RC buildings and the consequences of creep and shrinkage. The time period used for structural design and analysis is a crucial concern as most researchers have considered the response at the last stage of construction, i.e. at the application of live load. In order to evaluate that, this study observes two types of responses, the axial shortening and the bending moments for different time periods. The results were compared with the reference results for the 50th year, as RC structures in India are designed for a 50-year life span. The different time periods considered are 365 days, 730 days, 1000 days, 1825 days, 3650 days, 7300 days, 10950 days, 14600 days, and 18250 days from the application of live load, of which the optimal timespan is derived.

Since the CSAcs method is complicated, it is imperative to formulate a critical storey limit, i.e. “a limit for the total numbers of storeys of a building above which the CSA method is recommended”. In order to formulate that, this study calculates the percentage difference between the axial strains of vertical members using the CSA method for the critical time period as derived in this study (CSA_{30cs}) and the LSA method at every floor level of selected building models. Based on the percentage difference in axial strain obtained by the CSA_{30CS} method to the LSA method (Δ), columns are divided into different categories, and a critical storey limit for CSA method is recommended for all categories of columns. Twelve RC moment framed building models with RC shear walls of the same plan area but of different spans and total storeys were selected to evaluate the effect of various beam spans and total storey numbers on the critical storey limit. The building models were analysed with the help of Midas Gen 17 [11] software. This study's analysis and design are undertaken as per the Indian standard code of practice.

2. Materials and Methods

2.1. Building Models

A 40-story RC framed building with a 5m X 5m beam grid and plan dimensions of 25m X 25m was chosen to study the combined effect of creep and shrinkage on time span with CSAcs, as illustrated in Fig. 1(a) and Table 1.Twelve building models of symmetrical plan with a central shear wall with a floor height of 3.2m were selected to study the critical storey limit. Hence, three RC moment framed building models of the same plan area of 40m X 40m, but varying plan grids and total numbers of storeys, as shown in Table 1 and Fig. 1(b)-1(d), were selected. Models were initially analysed and designed using the LSA method and the Indian Standard Code of Practice, with live load of 3 kN/m^2, floor finishing load of 1 kN/m^2, and brick wall load of 5 kN/m. The cross-sections of structural members for the A40, B40 and C40 models are shown in Table 3. Similarly, the structural elements are designed for other models through LSA and used for the CSAcs method. Properties of the grade of concrete and steel used for the modelling of buildings are mentioned in Table 2.

Table 1. Description of the selected RC frame building model

Models	Plan size, mxm	Type of plan	Beam grid, m x m	Total storey numbers
A0	25 X 25	Plan A0	5 x 5	40
A40	40 X 40	Plan A	8 X 8	40
A30	40 X 40	Plan A	8 X 8	30
A20	40 X 40	Plan A	8 X 8	20
A10	40 X 40	Plan A	8 X 8	10
B40	40 X 40	Plan B	5.72 X 5.72	40
B30	40 X 40	Plan B	5.72 X 5.72	30
B20	40 X 40	Plan B	5.72 X 5.72	20
B10	40 X 40	Plan B	5.72 X 5.72	10
C40	40 X 40	Plan C	4.44 X 4.44	40
C30	40 X 40	Plan C	4.44 X 4.44	30
C20	40 X 40	Plan C	4.44 X 4.44	20
C10	40 X 40	Plan C	4.44 X 4.44	10

Table 2. Properties of materials used in modelling

Material properties	Reinforcement grade -Fe 415	Concrete grade -M 25
Yield Stress	415 N/mm^2	-
Compressive strength	-	25 N/mm^2
Modulus of Elasticity	2X10^5 N/mm^2	2.5X10^4 N/mm^2
Weight per unit volume	76.973 kN/m^3	23.6 kN/m^3
Poisson's Ratio	-	0.2

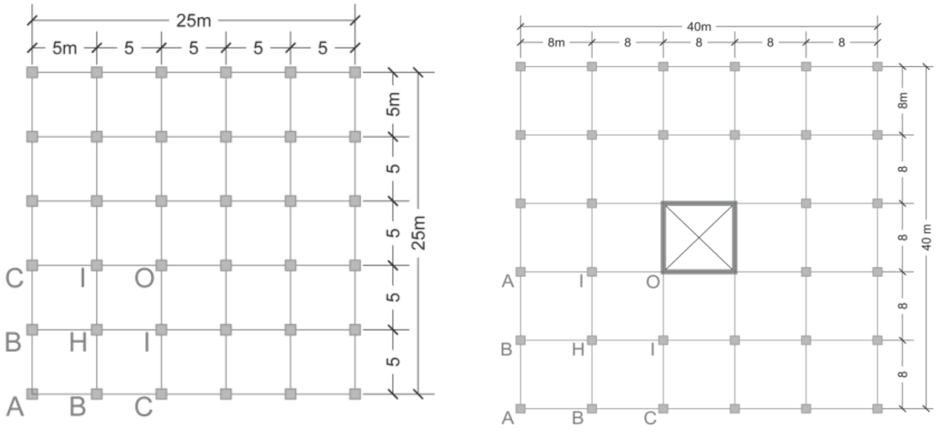
Table 3. Cross-sections of members

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

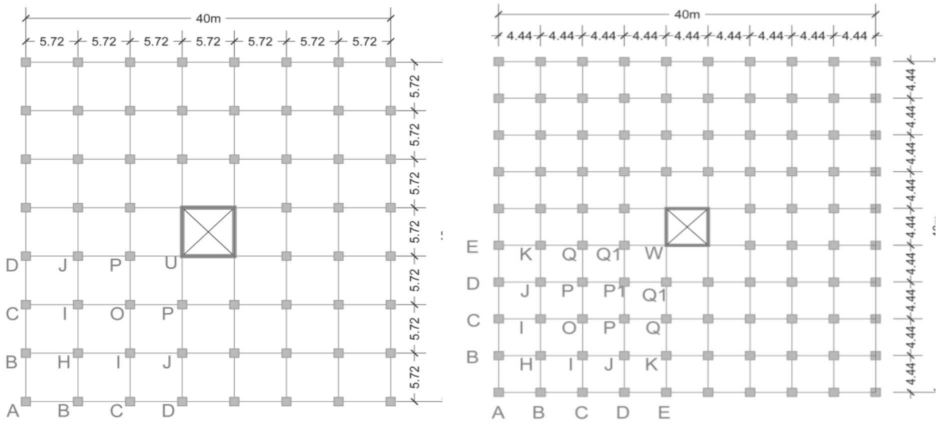
2.2. Material Properties Related to Creep & Shrinkage

To calculate the long-term shortening due to creep and shrinkage, IRC: 112-2011 code is used, wherein basic equations for creep co-efficient and the drying shrinkage strain are given. 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 are all factors taken into account when calculating the co-efficient of creep. While the parameters considered for calculation of the shrinkage strain are mean compressive strength, type of cement, and relative humidity.

2.3. Sequential Loads on Building Models



(a) Plan A0_25m x25m (b) Plan A models_ A40,A30,A20,A10



(c) Plan B models_ B40,B30,B20,B10 (d) Plan C models_ C40,C30,C20,C10

Fig. 1 Plan of different 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. For the first slab casting, the formwork was undertaken 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 up to 50 years of a lifetime after occupancy to get a critical time period for A0 building. The analysis was undertaken for 10950 days for twelve models to get critical storey numbers of the RC buildings.

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

3.1. Critical Time Period

CSAcs is carried out for the 'plan A0' building model. Total axial shortening for all columns were observed. Fig. 2 shows the shortening of column CA at the top floor level at the time of application of live load and for other time periods, which were 365 days, 730 days, 1000 days, 1825 days, 3650 days, 7300 days, 10950 days, 14600 days, and 18250 days from the application of live load by CSA method. The results of axial shortenings for all time periods were compared with the result of the 50th year.

Axial shortening at the top floor of column A was found to be only 14.28mm at the time live load was applied. In contrast, axial shortening was found to be much larger at 57.08mm after 50 years of live load application. After applying the live load at the top floor of CA, the axial shortening was 24.1mm, 41.53mm, 47.1mm, and 54.31mm after 365days, 1000days, 1825days, and 7300days, respectively.

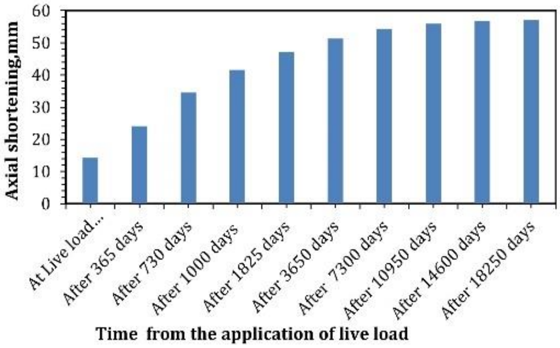


Fig. 2 Axial shortening of column A for the various time period

The findings of the percentage shortening of each column for each time period were compared to the percentage shortening of the 50th year as the base time period to determine the average percentage shortening of all columns, which was then plotted in Fig. 3. (a). Considering the axial shortening as 100 % in all columns after 50 years, the average axial shortening at the moment of live load application was observed to be 51.57%. The average axial shortening was reported to be 61.76%, 82.21 %, 88.55%, and 98.7% for the 50th year, respectively, during periods of 365 days, 1000 days, 1825 days, and 10950 days following the application of live load.

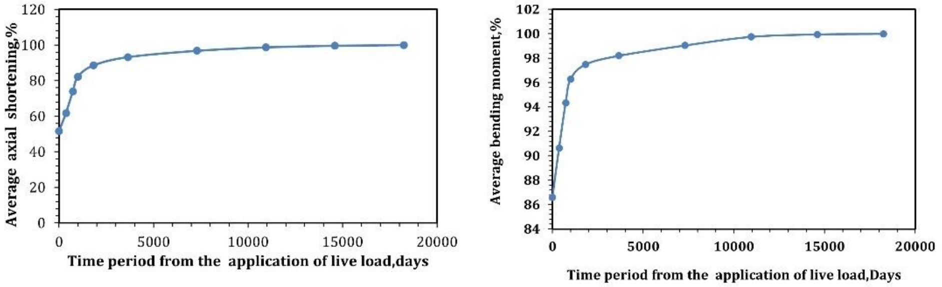
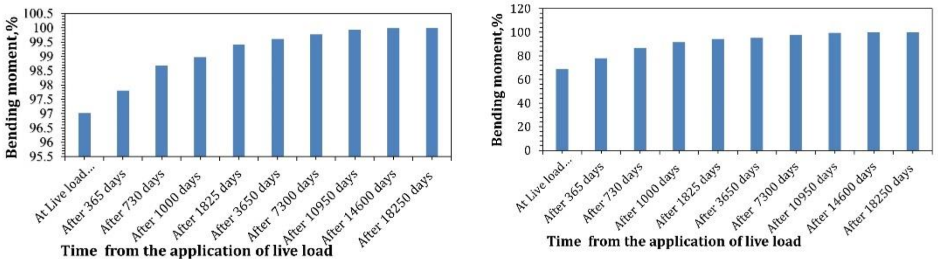


Fig. 3(a) Average axial shortening of columns w.r.t 50 years Shortening

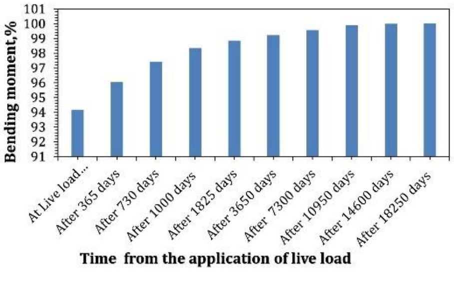
(b) Average bending moment of beam'AB' w.r.t 50 years bending moment

As seen in Fig. 1(a), beam "AB" of "plan A0" is chosen for observation. For every floor level and across all time periods, bending moments were noted at the ends "A," "B," and "AB." The average percentage moment of all floors for each time period, maintaining the 50th year as a base, was calculated at both the supports and mid-span of beam ‘AB’ and plotted in Fig. 4.



(a) Bending moment at end ‘A’

(b) Bending moment at end ‘B’



(c) Bending moment at mid-span

Fig. 4 Percentage moment at various locations of beam ‘AB’ for different time periods

The average moment observed at the time of live load application at end A, end B, and mid-span was 97.02%, 68.63% and 94.15%, respectively, if the bending moment in a beam after 50 years is deemed to be 100%.The average moment at every floor level was observed to be 90.6%, 94.3%, 96.3%, and 99.7% of the axial shortening of the 50thyear; after 365, 730, 1000 and 10950days time period respectively, as in Fig. 3(b).

3.2. Derivation of Critical Storey Limit

As per the time period study, 98.7% of axial shortening and 99.43% of bending moments of the 50th year were observed after 10950 days. Hence, all twelve models were analysed for 10950 days using the CSA method considering the long-term effects of concrete (CSA_{30CS}).

3.2.1 Categorization of Columns

An axial shortening, at every floor level (i), for all twelve building models by CSA_{30CS} method was compared with the LSA method., The ‘Δ’ parameter was introduced to compare the sensitivity of columns in terms of percentage strain difference induced due to the axial shortening in both methods. The following equation specified the percentage difference (Δ) induced in the axial strain at any floor level-‘i'.

‘Δ’ at any floor level

$$i=\left|\frac{Strain\ induced\ at\ i^{th}\ floor\ \ by\ CSA30CS-Strain\ induced\ at\ i^{th}\ floorby\ LSA}{Strain\ induced\ at\ i^{th}\ floor\ by\ LSA}\right| 100 \qquad (1)$$

Where strain induces at each floor level, (i^{th} level) =

$$\left|\frac{[Total\ Axial\ shortening\ induced\ at\ upper\ floor-Total\ Axial\ Shortening\ induced\ at\ lower\ floor\ level]}{Floor\ height\ (Hi)}\right| \qquad (2)$$

A graph representing the ‘percentage strain difference (Δ) V/S floor number’, for all vertical members of the A30 building model was plotted as shown in Fig. 5. Following observations were made from Fig.5.

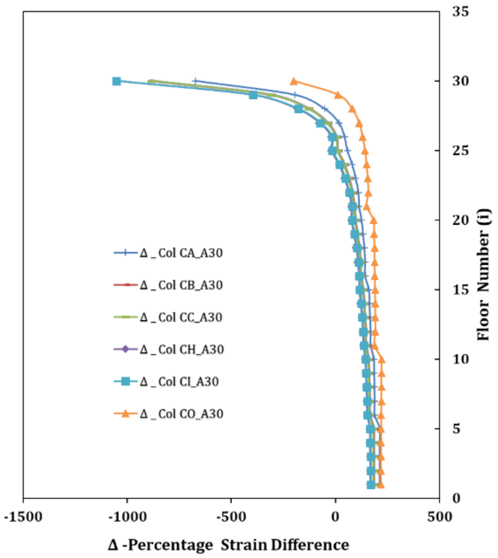
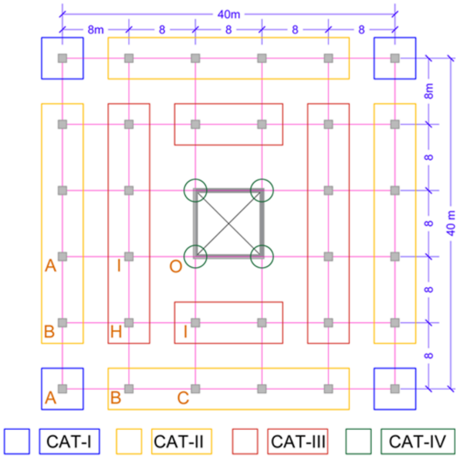


Fig. 5 Δ- percentage strain difference V/S floor number, for model A30

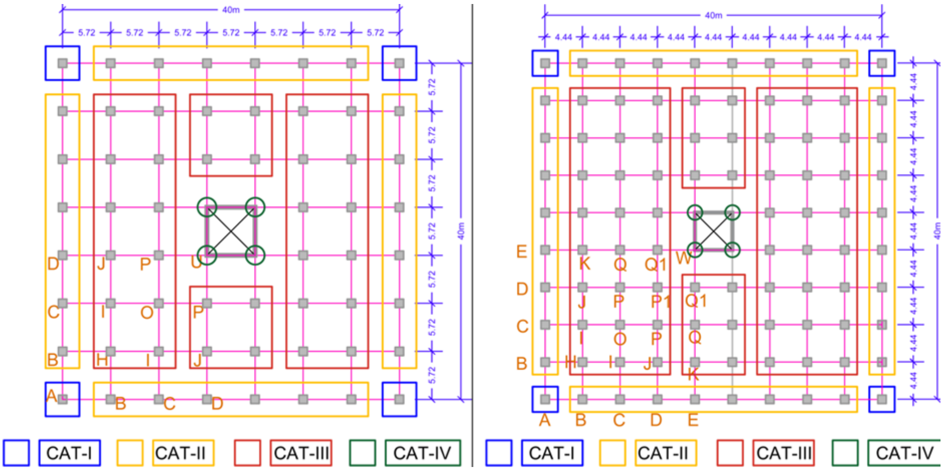
- Percentage strain v/s floor graph of columns CB and CC were similar.
  Percentage strain v/s floor graph of columns CH and CI were similar to Δ.
- Percentage strain v/s floor graph of columns CA and CO were independent of all columns.

Based on these observations, columns of the A30 were divided under four different categories, CAT-I, CAT-II, CAT-III and CAT-IV, as shown in Fig. 6(a).

Similar pattern of graphs was observed with the A40, A20 and A10 models, as shown in Fig. 7(a). Hence the columns were divided into four similar categories, as shown in Fig. 6(a)



(a) Plan A model

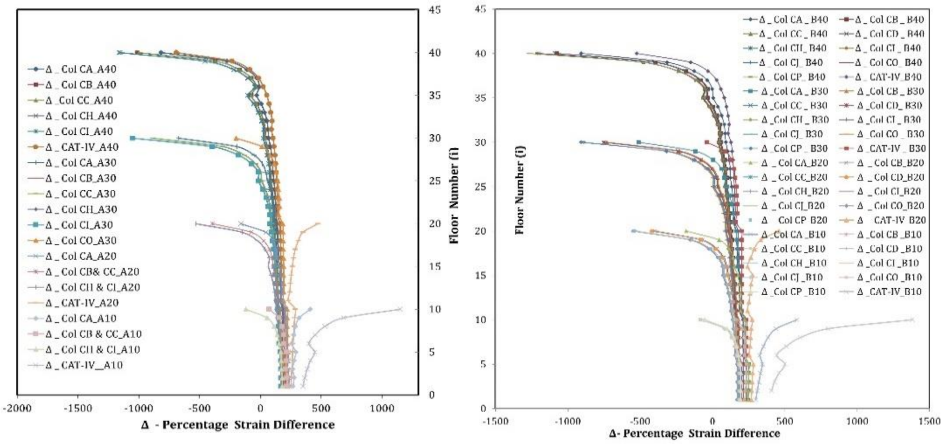


(b) Plan B model (c) Plan C model

Fig.6 Different categories of columns of plan A ,plan B and plan C models

- It was observed that the sensitivity of the axial strain increases as the building floors increase, as shown in Fig. 7(a) for models A40, A30, A20 and A10.
- Δ for the same column CA was higher in model A40 than in model A10 as shown in Fig. 7(a). As the building's total storey (n) increases, Δ of the column in all categories also increases.
- Maximum variation of Δ was observed within upper 15% to 18% storeys, as shown in Fig. 5 and Fig. 7.

The analysis and observations remain similar for plan B and plan C building models. Hence, all the columns were divided into four similar categories, CAT-I, CAT-II, CAT-III and CAT-IV, as shown in Fig. 6.



(a) plan A models (b) plan B models

Fig. 7 'Δ -percentage strain difference V/S floor number'_ for plan A and plan B models

3.2.2. Critical Storey Limit of RC Buildings with CSA30CS

It was observed from Fig. 5, Fig. 7, and Table 4 that maximum Δ occurs at the top-most floor level of the building models for all plans and categories of columns. Δ for CAT-I columns for all plan models are as in Table 5.

Table 5. Maximum percentage strain difference (Δ) for CAT-I columns

Building models	Maximum Δ, for columns of CAT-I					
	Plan A		Plan B		Plan C	
	maximum Δ	location	maximum Δ	location	maximum Δ	location
40 storeyed	-818.062	at 40th floor	-906.137	at 40th floor	-806.744	at 40th floor
30 storeyed	-672.761	at 30th floor	-510.508	at 30th floor	-525.674	at 30th floor
20 storeyed	-162.564	at 20th floor	-182.434	at 20th floor	-114.077	at 20th floor
10 storeyed	410.376	at 10th floor	583.192	at 10th floor	574.01	at 10th floor

The CAT-I columns for models C40, C30, C20 and C10 were also studied. The results were plotted in the 'Δ V/S floor number' graph, as shown in Fig. 8. An equation for floor sensitivity limit was extracted by drawing the best-fitted curve using a polynomial model passing through maximum Δ for CAT-I columns of plan C. The extracted equation of storey sensitivity for CAT-I columns of the plan C building model is:

'$n = 1E\text{-}05 * \Delta^2 - 0.019 * \Delta + 17.421$.'

As seen in the equation and Fig. 8, when the best-fitted curve crosses the vertical axis, the value of Δ becomes zero, and the corresponding total storey number (n) approaches 17.24. Hence this shows that when the CSA30CS method is used, the columns of CAT-I become sensitive when plan C type buildings cross 17 storeys (n). Similarly, plan C's columns of CAT-II, CAT-III & CAT-IV were also analysed. Critical storey limit equations were derived based on the graphical representation of the analysis as plotted in Fig. 9(a)-9(c). The extracted equations for storey sensitivity of CAT-II, CAT-III, and CAT-IV columns of plan C models are tabulated in Table 6.

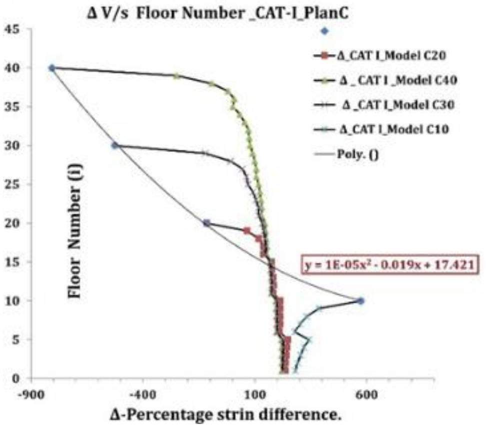
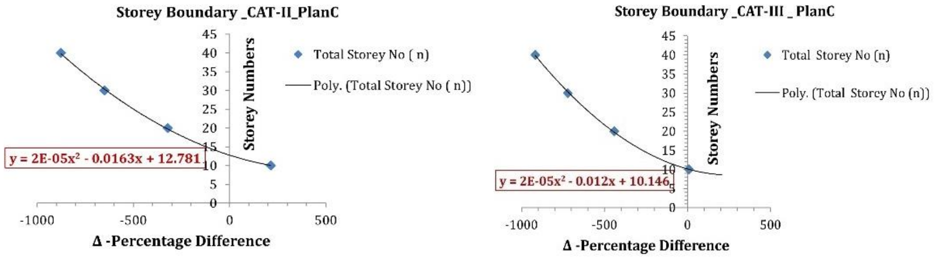
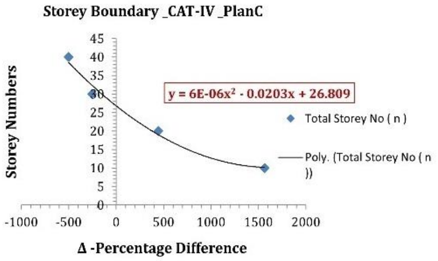


Fig. 8 Critical storey limit for CAT-I columns of plan C



(a) CAT-II of plan C

(b) CAT-III of plan C



(c) CAT-IV of plan C

Fig. 9 Critical storey limit for columns of plan C.

Similarly, equations for all categories of columns were extracted for plan A and plan B type building models as shown in Fig. 10(a)-10(d), and Fig. 10(e)-10(h),as tabulated in Table 6.

The average critical limit is the storey above which it is advisable to use CSA$_{30CS}$ method for the design of RC buildings. Average critical limits for all categories and models are tabulated in Table 7.

The observation for the above analysis is summarized as follows,

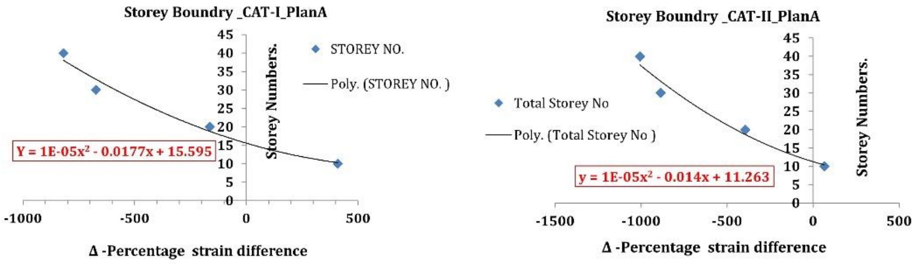
- In a building with storeys more than 16.82, CAT-I columns will be critical.
- In a building with storeys more than 12.13, CAT-II columns will be critical.
- In a building with storeys more than 9.27, CAT-III columns will be critical.
- In a building with storeys more than 27.51, CAT-IV (shear wall) will be critical.

Table 6. Equations of critical storey limit for all categories and columns

Column category	Equation	Sensitivity, in terms of 'n'
	For plan A	
CAT-I	$n = 1E{-}05*\Delta^2 - 0.0177*\Delta + 15.595$	15.595
CAT-II	$n = 1E{-}05*\Delta^2 - 0.014*\Delta + 11.263$	11.263
CAT-III	$n = 1E{-}05*\Delta^2 - 0.0132*\Delta + 8.8111$	8.811
CAT-IV	$n = 2E{-}06*\Delta^2 - 0.017*\Delta + 27.108$	27.108
	For plan B	
CAT-I	$n = 8E{-}06*\Delta^2 - 0.0179*\Delta + 17.46$	17.46
CAT-II	$n = 9E{-}06*\Delta^2 - 0.0164*\Delta + 12.348$	12.348
CAT-III	$n = 7E{-}06*\Delta^2 - 0.0178*\Delta + 8.6237$	8.624
CAT-IV	$n = 5E{-}06*\Delta^2 - 0.0198*\Delta + 28.612$	28.612
	For Plan C	
CAT-I	$n = 1E{-}05*\Delta^2 - 0.019*\Delta + 17.421$	17.421
CAT-II	$n = 2E{-}05*\Delta^2 - 0.0163x + 12.781$	12.781
CAT-III	$n = 2E{-}05*\Delta^2 - 0.012*\Delta + 10.146$	10.146
CAT-IV	$n = 6E{-}06*\Delta^2 - 0.0203*\Delta + 26.809$	26.809

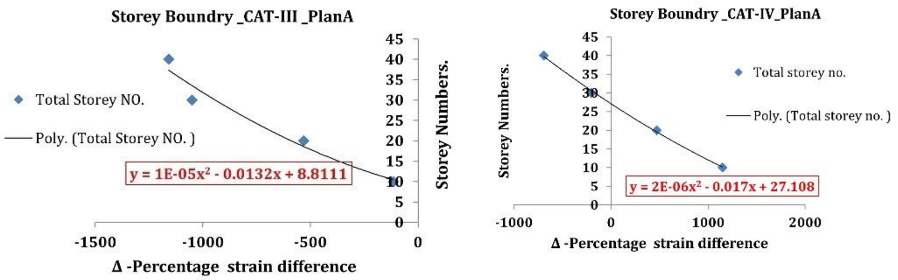
Table 7. Average critical storey limit for columns of all categories and all plans

Column category	Critical storey limit in terms of total storey numbers (n)			
	Plan A	Plan B	Plan C	Average 'n'
CAT-I	15.595	17.46	17.421	16.82
CAT-II	11.263	12.348	12.781	12.13
CAT-III	8.811	8.624	10.146	9.27
CAT-IV	27.108	28.612	26.809	27.51



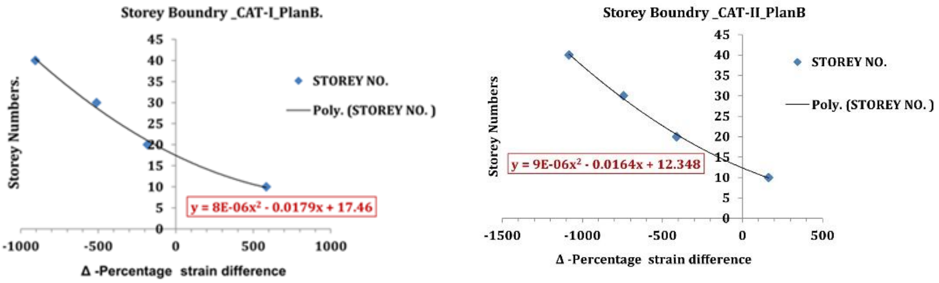
(a) CAT-I of plan A

(b) CAT-II of plan A



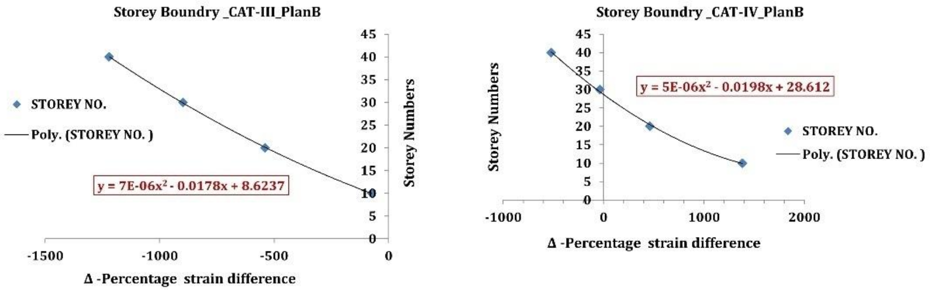
(c) CAT-III of plan A

(d) CAT-IV of plan A



(e) CAT-I of plan B

(f) CAT-II of plan B



(g) CAT-III of plan B

(h) CAT-IV of plan B

Fig. 10 Critical storey limit for columns of plan A and plan B

4. Conclusions

This study determines the critical time period up to which the CSA method should be used to analyse and design the RC framed buildings. Furthermore, it determines the critical storey limit for the RC framed building, over which the CSA method must be used. It is concluded that:

- The rate of axial shortening increase for the first 7300days is significant compared to the days between 7300, i.e., 30 years to 18250 days i.e., 50years, when the analysis is done through the CSA method.
- Only 51.57% of the 50th year axial shortening is achieved at the time of live load application, which is only half of the critical shortening observed at the 50th year.

Whereas 86.6% of the 50th year beam moment is achieved at the time of live load application, which is less than the critical moment observed at the 50th year.

- 98% to 99% of the total 50th year axial shortening and beam moments are observed on completion of 7300days (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.
- Behavioural patterns of columns for all building models of various spans and total storeys are divided into four categories. Each category has its own critical storey limit. Hence, if the column crosses this limit, the CSA$_{30CS}$ method must be adopted for the analysis and design of the column instead of the conventional –Linear Static Analysis method for a safe design.
- It is observed that maximum percentage strain difference (Δ) occurs at the top most floor level of a building for all plans and categories of the column. Maximum variation of percentage strain difference (Δ) is observed in the upper 15% to 18% of total storeys.
- As the total storey (n) of a building increase, the percentage difference in strain (Δ) in a column also increases for all categories of columns in building models.
- If the total number of stories is more than or equal to 16, columns of category -I become critical. Similarly, category – II, III & IV columns become critical if the total number of stories is equal to or more than 12, 9, and 27, respectively. Thus, for a building with a total storey number of more than nine storeys, the CSA$_{30cs}$ method should be mandatory to analyse and design RC framed buildings.
- The reduction in the span of beams results in an increase in critical storey limit for all categories of columns.
- The critical storey limit of the shear wall is higher than that of columns.

Acronym

CSA$_{CS}$: Construction Sequence Analysis considering creep and shrinkage

CSA$_{30CS}$: Construction Sequence Analysis considering creep and shrinkage (CSACS), up to 10950 days (30 years) from the time of live load application

LSA : Linear Static Analysis Method

Δ : A percentage difference in axial strain, obtained by the CSA30CS method with respect to LSA method

CA, CB : Column A, Column B, etc

RC : Reinforced Concrete

n : Total storeys in building

i : ith floor level

wrt : with respect to

CAT : Category

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