The International Journal Of Engineering And Science (IJES)
||Volume||3 ||Issue|| 1||Pages|| 52-63||2014||
ISSN(e): 2319 – 1813 ISSN(p): 2319 – 1805

Chronological Construction Sequence Effects on Reinforced Concrete and Steel Buildings

Yousuf Dinar[1], Munshi Md. Rasel[2], Muhammad Junaid Absar Chowdhury[2], Md. Abu Ashraf[3]

[1, 3] Department of Civil Engineering, University of Asia Pacific, Bangladesh
[2]Department of Civil Engineering, Ahsanullah University of Science and Technology, Bangladesh
[2]Prodigy Architects and Engineers Limited, Bangladesh

--ABSTRACT--

Building structures are analyzed in a single step using linear static analysis on the assumption that the structures are subjected to full load once the whole structure is constructed completely. In reality the dead load due to the each structural components and finishing items are imposed in separate stages as the structures are constructed story by story for nonlinear behavior of materials. Advancement of finite element modeling accelerates the accuracy of finite element simulation by taking the consideration of construction sequential effects. In this paper, rigid frame structures of both concrete and steel model of different configurations have been taken for sequential analysis. The analysis outcomes will help to understand how the structural response against loads varies for construction sequential analysis and linear static analysis while highlighting the material property. For vivid understanding of necessity of sequential analysis, analysis outcomes are eventually compared with conventional one step analysis. The effect of sequence of construction due to the self-weight of members has been studied and its effect on the overall design forces has also been highlighted using finite element modeling.

KEYWORDS *: Nonlinear behavior, finite element modeling, construction sequential, sequential analysis, structural response*

Date of Submission: 10 January 2014 ⟺ Date of Acceptance: 25 December 2014

I. INTRODUCTION

Generally engineers, researcher and decision makers have determined the behavior of structures using linear static elastic finite element analysis including summations of vertical column loads. While building height increases in construction phase, the structural responses, i.e. axial loads, bending moments and displacements, of such typical analysis may increasingly diverge from actual behavior. Time-dependent, long-term, deformations in response to construction sequence can cause redistribution of responses that would not be computed and considered by conventional methods. This analysis was complex in nature and so many parameters have to be taken into account during analysis. But now advancement of finite element modeling and simulation has made nonlinear analysis easy, well managed and popular among engineers, researchers and decision makers which accelerate proper design of structures especially high-rise. Construction sequential analysis is becoming an essential part during analysis as many well recognized analysis software included this facility in their analysis and design package. However this nonlinear static analysis is not so popular because of lack of knowledge about its necessity and scope. Like so many other analysis, construction sequential analysis have specific purposes in design phase of the structures. As it is mentioned earlier, it deals with nonlinear behavior under static loads in the form of sequential load increment and its effects on structure considering the structural members are started to react against load prior of completing the whole structure. For finite element analysis one of the leading analysis software "ETABS (Extended 3D analysis of building systems) Version 9.7.2" is used and all displacement outcomes are measured in mm while moment and axial load are measured in kip-ft and kip respectively.

II. SIGNIFICANCE OF STUDY

While constructing High-rise the self-weight of its own become a considerable fact and during design and construction sequential analysis consider the chronological construction phases which consider the residual stress of each story of the structure separately step by step to view the final displacement and other responses. Generally it causes greater displacement and greater structural effects for nonlinear behavior of materials than the simple linear static analysis. As linear static counts the total effect of the final stage of the construction without considering step by step nonlinear effects for sequential construction, the output are not reliable for high-rise. Lacking of knowledge about nonlinear behavior of materials and sequential analysis pushes to the inappropriate design which may causes catastrophic destruction of structures. It becomes obligatory to perform construction sequential analysis for high-rise. This study identify how construction sequential analysis effects the variation of structural responses i.e. displacements, axial forces and moments from the so called one step analysis- "Linear Static analysis" for two major construction material- steel and reinforced concrete. Research findings will highlight the necessity of sequential analysis for high-rise by explaining the degree of variation of responses for sequential analysis and linear static analysis.

III. LITERATURE REVIEW

In year 1978 S.C Chakrabarti, G.C. Nayak and S.K. Agarwala have researched on construction sequential analysis for multistoried building frame for self-weight only. In 36 year intervals the structural analysis software are improved to perform this sequential analysis properly by finite element modeling. A significant research on a catastrophic collapse of this sequential effect is the earth quack of Kiholo which bring attention of researchers, engineers and decision makers on this. In 2006 Kiholo Bay earthquake on the "Big Island" of Hawaii, a unique cracking pattern, different from others, was observed in an iconic 1960s reinforced lightweight concrete building. To determine the cause of this unique cracking, a nonlinear finite-element model was developed using the Adina analysis program. In the analyses, the construction sequence and expected shrinkage were modeled. Besides that nonlinear static pushover was also performed using the Capacity Spectrum Method. The analyses demonstrated that a state of sustained tensile stress created from the construction sequence offered the best explanation for this unique cracking pattern. [1] While designing the world largest structure (till 2014) this analysis is performed during analysis phase along with other analysis. To account this nonlinear time dependent concrete effects in the Burj Dubai, construction sequence analysis incorporating the effects of creep and shrinkage was utilized to study the time-dependent behavior of the structure (Baker et al., 2007) Figure 1.[2],[3]

(a) Step by step of Model of construction sequential analysis of Burj Kalifa

(b) Whole model of Linear Static analysis model of Burj Kalifa

Figure 1: Construction sequential and linear static analysis of Burj Dubai

Photo Credit: William F. Baker, D. Stanton Korista and Lawrence C. Novak (2008)

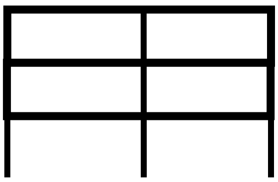
Due to lacking of adequate research this facts are still undercover from general construction engineers both for reinforced concrete and steel structures. This research will act like a general non-specialized outline to get experience about construction sequential analysis for both two major materials including the P-Delta effects, creep and shrinkage consideration in the analysis.

IV. RESEARCH METHODOLOGY

The strength, stability and deflection checks in the conventional design which consider linear static analysis are based on the whole structure not considering the sequential process. In reality, the behaviour of the components or units in the erection process is different from the ideal case because instability and excessive deflection occur in the construction stage with limited propping. Furthermore, shortening and undesirable deformations of the incomplete structure under self-weight and construction loads are inevitable. The structural self-weight, external loads, boundary conditions and materials are depended on stages during the construction process and their variations are overlooked in conventional design which is nothing but a limitation of conventional design procedure. Grouping of each story is considered during analysis so that software can identify its total steps required for completing the procedure. Step by step analysis, considering nonlinear behavior of materials from previous step, ensures that the construction sequence effects are properly represented in the study. Recording and investigating the variation of responses, of a particular point from starting step of sequential analysis to the last one, exhibit how construction sequence has a well impact over the design of the structures. Afterward the comparison between the findings of construction sequential analysis and linear static analysis will explain the importance of considering sequential effects during design and eventually meet the objectives of this study.

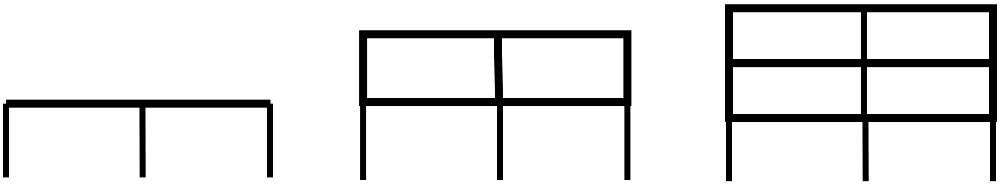
V. DESCRIPTION OF CONSTRUCTION SEQUENTIAL ANALYSIS

In short, linear static analysis is performed in one step while construction sequential analysis is performed in a manner, after each story construction like the real condition Figure 2. A comprehensive sequential analysis involves some essential steps which are not generally performed during linear static analysis. In order to get the sequential effects manually using software, each story should be analyzed with its prior stories assigning the vertical and lateral loads till that floor from bottom of whole structure. Eventually outcomes will represent the structural response of building till that floor. Once each story follows the same procedure the complete sequential effects could be visualized. Now-a-days analysis software are sufficiently developed to auto perform the sequential analysis easily. In this procedure, after assigning vertical and lateral loads each story is grouped to command the software to perform the analysis till that particular floor from bottom while avoiding higher story than that floor. After grouping the software eventually ask for which facility should be taken and then the outcomes could be comparing among different conditions.



Step 1: Full Story

(a) Linear Static analysis is performed in only one step while not considering the sequential construction of each floor

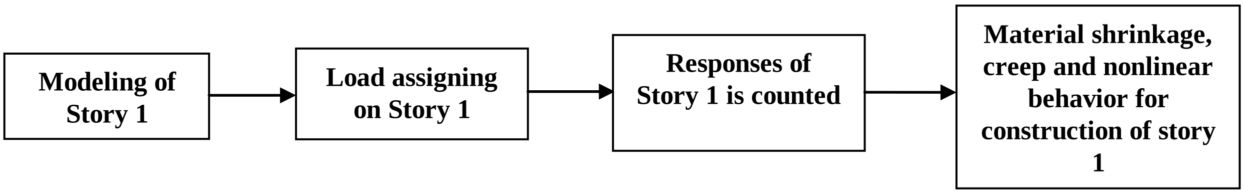


Step 1: Story 1 Step 2: Story 2

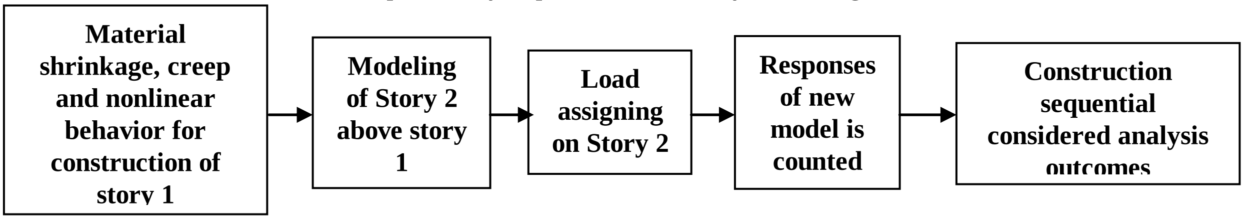
(b) Construction sequential analysis is performed after construction of each story like real scenario

Figure 2: Stage formation in Linear Static and Construction sequential analysis

The manual analysis procedure is summarized for a sample structure of two story only in Figure 3 which is limited into 2 step by its nature. Step of analysis will increase with the number of story to meet the demand.



Step 1: Analysis procedure for Story 1 buildings



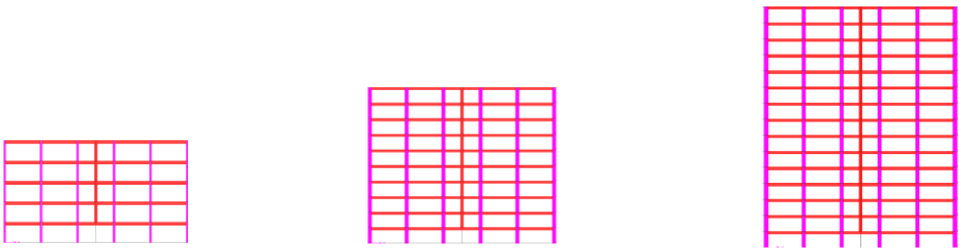
Step 2: Analysis procedure for Story 2 buildings

Figure 3: Steps involves in Construction sequential analysis of a typical two story building

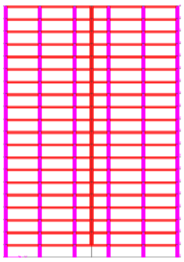
Construction sequential analysis deals with model effects of construction or demotion, specify active structure by stories or groups, geometric nonlinear P-Delta analysis and large displacements, sequential construction load cases for design and also the user defined loads. [4]

VI. FINITE ELEMENT MODELS FOR ANALYSIS

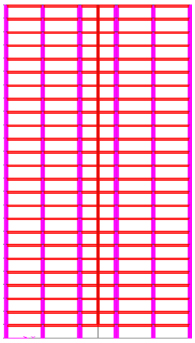
To observe the effects of nonlinear static analysis over linear static analysis finite element are formed using ETABS 9.7.2 where construction simulation analysis is included along with linear static analysis. To meet the objective, all loads and sections for both two material cases and two separate analysis procedure, are designed and taken carefully. A little divergence from actual style may leads to in appropriate modeling which cannot reflect the real situation. The time-dependent effects of creep, shrinkage, the variation of concrete stiffness with time, sequential loading and foundation settlement were accounted for by analyzing 12 separate three-dimensional finite-element analysis models, each representing a discrete time during construction on which six represent the sequential analysis while remaining six represent the linear static analysis. At each point in time, for each model, only the increasing loads occurring in that specific time-step were applied. The structural responses occurring at each time-step were accounted and added in a database to allow studying the predicted time-dependent response of the structure. To develop construction sequential effects in rigid joint structure six different story cases is taken where story variation starts from story 5 to story 30, boundary limit of rigid joint frame system. Making 5 story intervals from each makes a gradual but less time consuming analysis procedure as well. Story cases are: 5, 10, 15, 20, 25 and 30 Figure 4



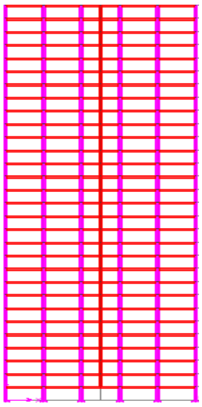
(a) Story 5 (b) Story 10 (c) Story 15



(d) Story 20



(e) Story 25



(f) Story 30

Figure 4: Six different model story cases: (a) Story 5, (b) Story 10, (c) Story 15, (d) Story 20, (e) Story 25 (e) Story 30

Each of the story case is performed Linear Static and sequential analysis separately with appropriate command. Each story is 3 meter in height makes Story 5, Story 10, Story 15, Story 20, Story and Story 30 in total height of 15 m, 30 m, 45 m, 60 m, 75 m and 90 m Figure 5 and Figure 6. As story increases so the

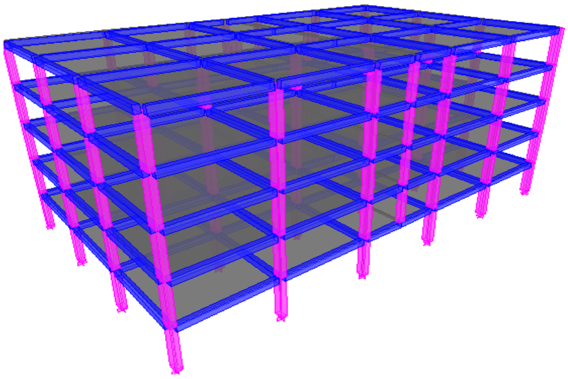


Figure 5: Three dimensional model of Story 5

slenderness increases. Bay length of buildings in both directions is 5 meter. The floors are assumed to be rigid in their plane. The lateral load seismic is considered in both directions of the structure using UBC94 by providing seismic coefficient of seismic zone 2, moderate risk rated arena of Bangladesh to perform both Linear Static and sequential analysis separately. Accidental load is taken into account for both two major analyses to ensure load eccentricities are considered in analysis.

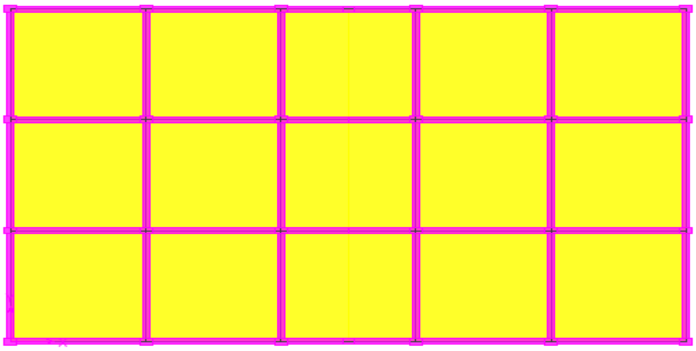


Figure 6: Typical plan of finite element models.

For the RCC model the column sizes are 305X 460 mm while situated in joint of each beam give compressive strength. Again, slab thickness is 152.4 mm reinforced concrete of 20.68 MPa (apparently 3000 psi) compressive strength. All beams and unsupported columns are of same size: 300X450 mm of 24 MPa (apparently 3500 psi) of compressive strength. Columns are also assigned less than 24 MPa of compressive strength. On the other side the steel model are assumed to section of A36 grade which put the yielding strength to 36 ksi keeping ultimate strength 58 ksi. For steel cases the shape is not changed to avoid shape factor and getting only material effects such as creep, shrinkage and nonlinear stress-strain behavior. The column sizes are still kept 305X 460 mm while situated in joint of each beam give compressive strength like the RCC cases. Here too, slab thickness is 152.4 mm reinforced concrete of 20.68 MPa (apparently 3000 psi) compressive strength similar to RCC models. All beams and unsupported columns are of same size: 300X450 mm of solid steel section. Other material properties are kept in the simulation model according to market availability, not specially improved Table II.

Table I
Material properties of the model

	RCC	Steel
Weight per unit Volume (pcf)	150	490
Modulus of Elasticity, E (ksi)	3600	29000
Poisson's ratio, υ	0.2	0.3
Co-efficient of thermal expansion	5.5×10^{-6}	6.5×10^{-6}
Shear modulus, G (ksi)	1500	11153

The model is assumed to be situated in Dhaka city so seismic zone 2 is taken according to Bangladesh National Building Code (BNBC). [5] Therefore, each column is subjected to both in compression and tension during the shaking in alternative sequence. Higher bending moment governs to the columns due to compression than the tension.

VII. RESEARCH CASES

Research objectives could be met by taking consideration of construction sequential analysis along with linear static analysis for structures of different story configuration of the selected materials: RCC and Steel Table II. In this study the effects of material, story variation and analysis will be visible to the researchers, engineers as well as the decision makers. Now to make the sequential effects governing in the structures, story cases are varied from story 5 to story 30 in an interval of 5 stories which eventually generates six story cases. For easy understanding P-Delta effects is assigned in analysis procedure.

Table II
Construction sequential analysis cases

	RCC		Steel	
	Construction Sequential analysis	Linear Static analysis	Construction Sequential analysis	Linear Static analysis
Story 05	Case 1	Case 7	Case 13	Case 19
Story 10	Case 2	Case 8	Case 14	Case 20
Story 15	Case 3	Case 9	Case 15	Case 21
Story 20	Case 4	Case 10	Case 16	Case 22
Story 25	Case 5	Case 11	Case 17	Case 23
Story 30	Case 6	Case 12	Case 18	Case 24

VIII. RESEARCH FINDINGS

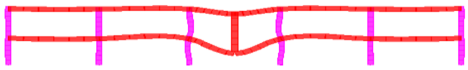
This paper presented the effects of chronological construction sequence of reinforced concrete and steel building with respect to linear static analysis. In the sequential analysis P-Delta effects of structure, shrinkage, creep and stress- strain behavior was reflected as results was quite different from outcomes of linear static analysis and this variation has tendency to decrement with the height. For comprehensive understanding of effects the finding could be categories in displacements, axial and moment. Each of those structural responses has a changing tendency with the change of analysis procedure and material. At first, how the evaluation takes place under construction sequential analysis is elaborated for easy understanding of how the imaginary study model have acted, in such way which represent real facts happen during construction. For this part of study, the model of only story 5 is used for short presentation and with the increment of story the effects will cumulatively added to the basic analysis which will eventually leads to more severe cases. Other research results are summarized into maximum vertical displacement in the hanging column, maximum axial load into column and moment in critical beam on which the column is hanging for describing the severity of the situation and the story moment of story 30 to describe how moment changes with construction of each new story against the linear static analysis. Outcomes of the research also represent the preference and suitability of material against construction sequential effects which is steel has displacement during analysis.

8.1 Development of sequential effects:

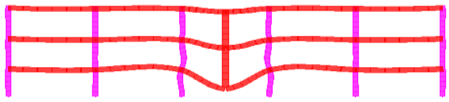
The differences in results become visible after performing linear static and nonlinear sequential analysis together that the each step of , multi-step involved, sequential analysis could be managed against one step involved linear static analysis. The structural responses such as displacement, moment and shear in a specific member of a specific floor start to vary from construction of first story which continue till fully construction of whole structure. During construction the new floor does not get the intact condition of its prior one Figure 7. For this section, the critical beam of story 5 in 1st floor, where a foundationless column is connected vertically, taken for clear and easy presentation of effects of construction sequential analysis Table III. A comparative view of each response may clear the severity as well as contribution material in this analysis.

(a) Step 1: No loading condition of story 1 of 5 story building

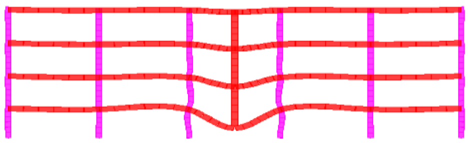
(b) Step 2: Loading condition of story 1 of 5 story building



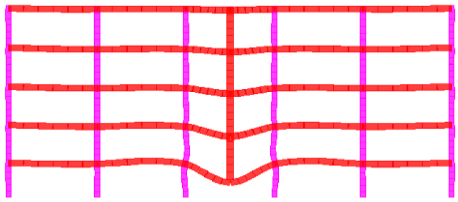
(c) Step 3: Construction of story 2 above story 1



(d) Step 4: Construction of story 3 above existing story 2



(e) Step 4: Construction of story 4 above existing story 3



(f) Step 5: Construction of story 5 above existing story 4

Figure 7: Steps involve in Sequential nonlinear analysis.

Table III
Structural responses of critical beam of case story 5

	Material	Construction Sequential analysis					Linear Static analysis
		Step 1	Step 2	Step 3	Step 4	Step 5/ Final Stage	
Moment (kip-ft)	RCC	42.5	67.69	85.4	99.12	112.22	60
	Steel	58.74	106.55	129.62	153	174.4	94.79
Shear (kip)	RCC	8.6	13.26	16.47	19.10	21.46	12.22
	Steel	14.89	22.67	28.07	32.48	36.39	22.14
Displacement (mm)	RCC	2.17	3.28	4.15	4.87	5.54	3.22
	Steel	1.37	1.89	2.59	2.97	3.67	1.63

After descriptive view of effects of chronological construction sequence analysis over static linear analysis one thing is well established that sequence effects has a worst side effect than static linear analysis and that is increasing structural responses i.e. moments, displacements or shear, with construction of new floor. For a detail explanation if 5 different construction stages is counted for a five story building, the result will not be same if the analysis is completed with only one stage what will be final one. Stage considerations have given moment of 112.22 and 174.40 kip-ft where the one stage considered analysis give 60 for 94.79 kip-ft, for RCC and Steel respectively. On the other side for shear and the displacement have the same under sequential effects, shows much value than the linear static analysis. We could say from stage 2 or after construction of 3rd floor the sequential effects become mentionable.

8.2 Displacement in critical beam:

After analysis it is seen in general trend of the all structural numerical model that steel structures are stiffer against load than the RCC structures as RCC structures show much displacement for both linear static cases and sequential analysis. In general, displacement from construction sequential analysis is high than linear static for several material related factors and time. However this variation between linear static and sequential analysis is similar for each story keeping the trend linear like unitary projection Figure 8 and Figure 9.

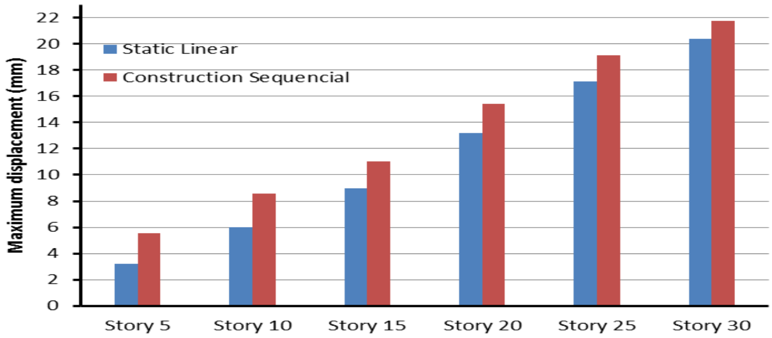


Figure 8: Maximum displacement of structures of RCC

The displacement of RCC (3500 psi) structures under sequential analysis for story 5 to story 30 in 5 story intervals varies from 5.7 to 19.7 mm for this types of structures where it varies only 2.5 to 20 mm during linear static analysis. As steel structures has a minimum displacement than the concrete structures it could be a better option to use steel structures for long term construction where incremetnal construction will have a less effects on the structure overall. When this types of structures are made by steel (A36) may show displacement 1.1 to 4.3 mm and 0.69 to 3.8 mm under sequencial and linear static analysis respectively, for the same structures.

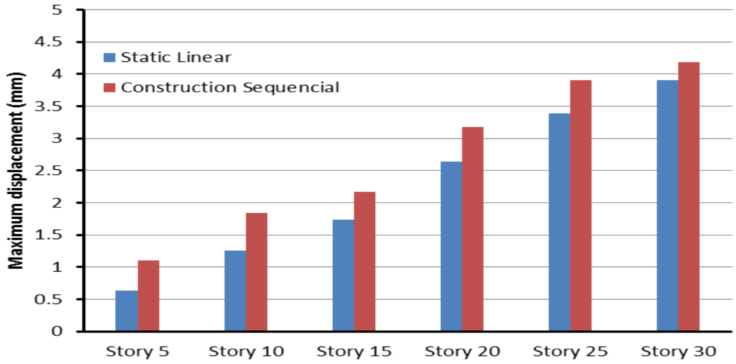


Figure 9: Maximum displacement of structures of Steel

8.3 Axial load in column near critical beam:

Axial load in exterior column has significant effects of both vertical and lateral load which make it a point of interest and need biaxial design. Like the displacement here too, Steel structures differ significantly from RCC structures. Steel structures are found bearing much loads than RCC which might be happen due to self-weight as unit weight of steel is 490 lb. per cubic ft Figure 10 and Figure 11.

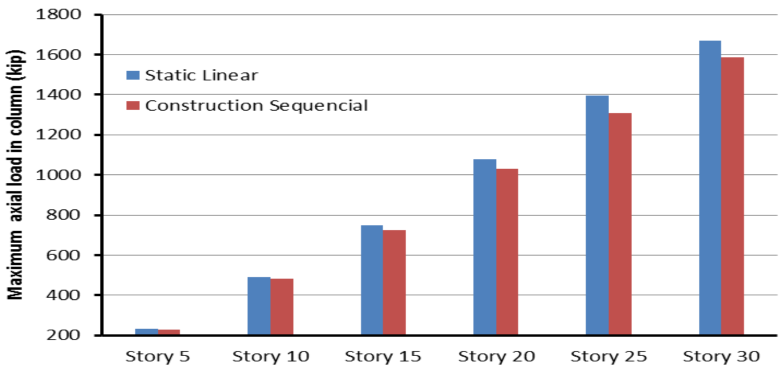


Figure 10: Maximum axial load in an exterior column for RCC structures

Another mentionable factor is that axial load, in column near critical beam, after sequential analysis is became lower in value than linear static for both RCC and Steel. This decreasing property is not found in moment, shear or displacement property.

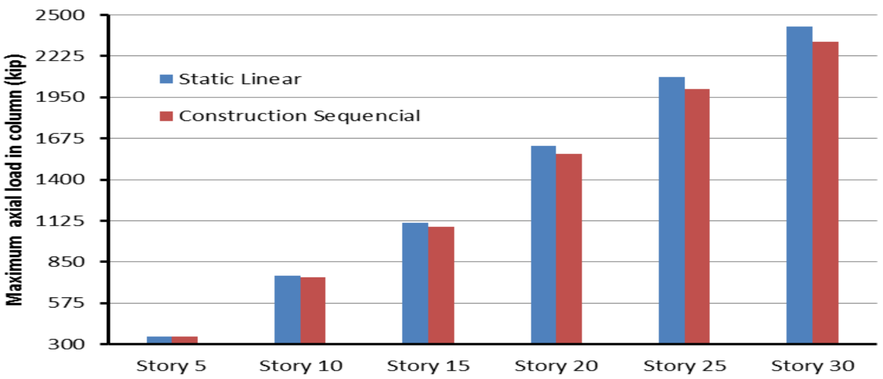


Figure 11: Maximum axial load in an exterior column for Steel structures

This phenomenon could be explained in such a way that under the construction sequential analysis, the effects of tension causing load in the beam become visible and the hanging column in critical beam gives tension in that beam which may eventually create a tension in inside side of the structure reduces axial load and dissipate among remote column Figure 12. The trend follows a unitary projection with the increment of story.

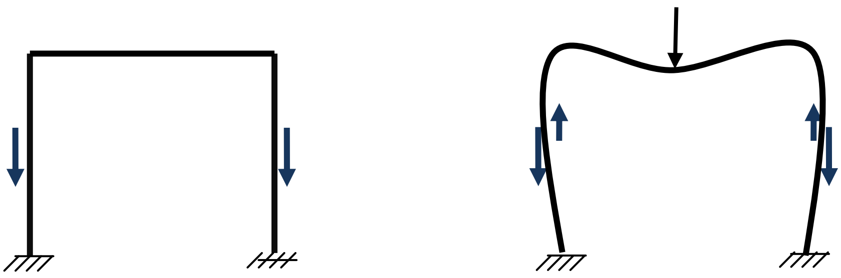


Figure 12: Effects of concentrated load from column

8.4 Moment in critical beam:

Axial load from hanging column may causes of destruction of the supporting beam. Construction sequential effects cause a significant change from linear static analysis. Construction sequence increases the moment as once the structure is being constructed effects of nonlinear factors i.e. creep, shrinkage and time dependent load govern Figure 13 and Figure 14.

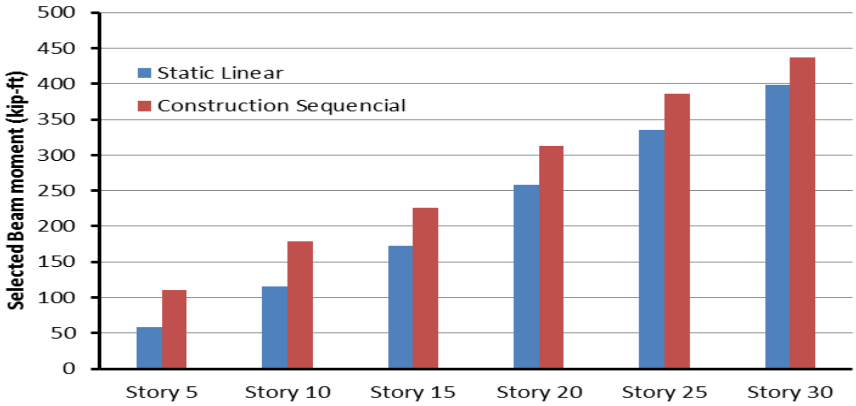


Figure 13: Maximum axial load in an exterior column for RCC structures

Moments in supporting beam are subjected to much more load under sequential analysis than the liner static analysis. Nonlinear material characteristics and time cause variation in building load taking capacity. It leads to increment of moment than the linear static analysis which reflects the birth time of the whole structure.

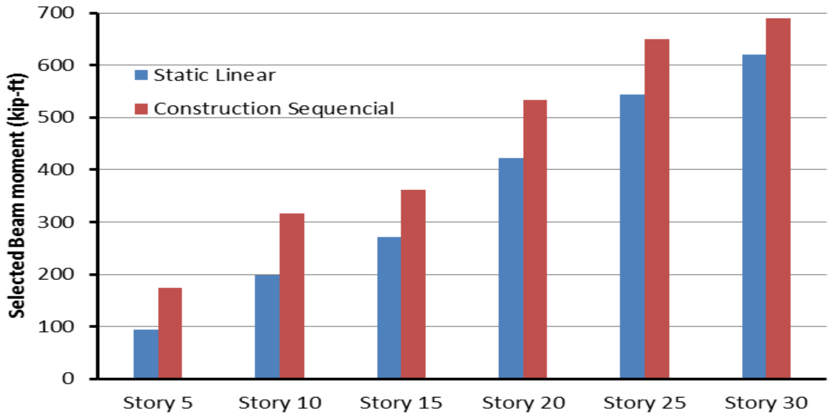


Figure 14: Maximum axial load in an exterior column for Steel structures

This section of analysis findings clear the fact that the steel structures takes much moment then the structures made of RCC. It makes the steel structures maximum moment resistant structure with low displacement than the RCC.

8.5 Story moment in exterior column:

Story moments will reveal the behavior of structures against moment for both materials under two analyses and judge the accuracy of real design works which may be completed without considering sequential effects. In general steel sections have much moment taking capacity then the RCC sections of same size and shape so shifting of moment curve to the upward is a general trend in both linear and this nonlinear analysis Figure 15 and Figure 16.

In this section of the finding story moment of each analysis of both materials have reflected some special characteristics or tendency in the study model, which may need to understand while designing structures, such as

[1] Construction sequence causes greater moment in structures of both material than the linear analysis

[2] The maximum moment occurs in middle portion approximately in the half of the structure and which is approximately same in value for both analysis procedures.

[3] Trend of story moment maintains much uniform steady increment or decrement characteristic for construction sequential analysis throughout the structure than the linear static analysis of the same structure.

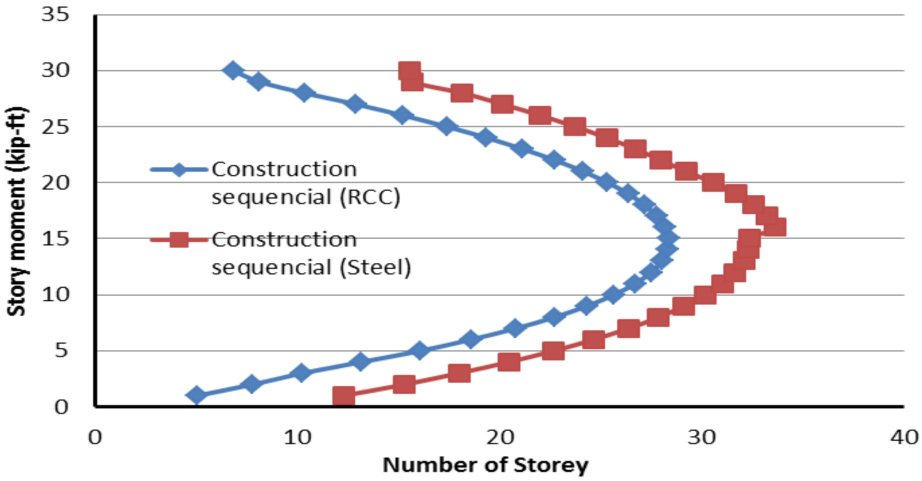


Figure 15: Story moment under Construction sequential analysis

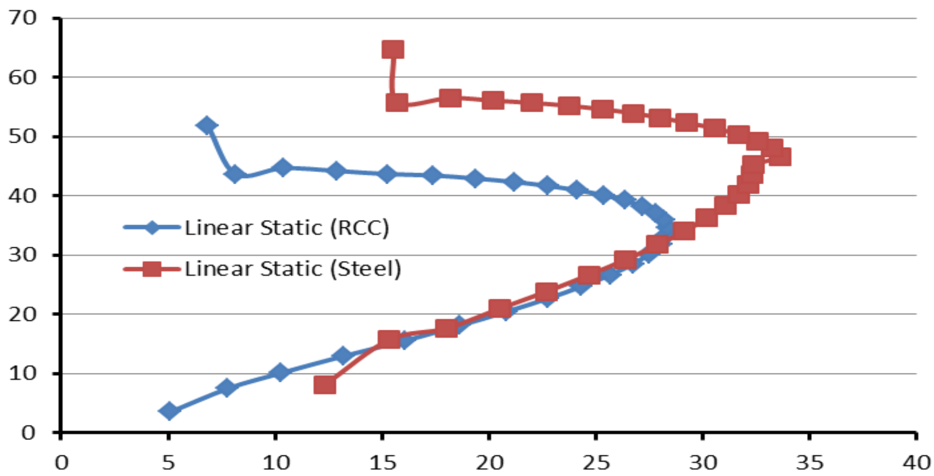


Figure 16: Story moment under Linear Static analysis

IX. CONCLUSION

The study reveals the necessity of performing nonlinear static analysis becomes important with increasing slenderness while the each additional floor creates a significant load upon the columns. With increasing slenderness the necessity to perform sequential analysis considering P-Delta effects, material characteristics and nonlinear of behavior of the structures become a significant issue. [6] Construction sequence analysis in structures of both Steel and RCC is necessary to improve the analysis accuracy in terms of displacement, axial, moment and shear force in supporting beam and column near of it and also for the whole the structure overall. Moments and shear in supporting beam are higher in sequential analysis which must be considered during manual or computer aided design in the design phase for avoiding cracking of beam and column due to sequence effects. Axial load may found lower after consideration of sequential effects but it should not be considered as to reach final stage each preliminary stage must be fulfilled and structures have to be designed strongly for each and every stage not the final one only. In the case of displacement sequence considered structure have much worst side condition than the linear static considered structures and it pushes toward the sequence considered. Analysis outcomes significantly changes to worst side under construction sequential analysis from the linear static analysis so to build a high-rise which involves construction of many floor and with longer time of construction sequential effects is obligatory to be considered. Construction sequential analysis also draws a preference of steel structures over the RCC structures for long term loading effects. Again an overall view on variation characteristics of structural responses of construction sequential considered outcomes over not considered outcomes is represented in Table IV. Maximum displacements in top and moments are used to change the percentage of variation so that necessity could be understood easily. It seems with the increasing story the variation decreases with the structures constructed with RCC where Steel does not follow any identical order in nonlinear analysis, needs more research on this part. However the varation is it should not be assumed during design and decision making phase.

Table IV
Percentage of variation of Structural Responses

		Story 5	Story 10	Story 15	Story 20	Story 25	Story 30
Displacement	RCC	132	41.67	30.95	15.38	11.76	7.92
	Steel	83.33	41.67	29.41	14.81	11.76	10.52
Moment	RCC	100	63.64	29.41	21.57	11.76	29.41
	Steel	89.47	55	35.71	26.2	23.1	13.11

In summary construction sequential analysis is an attempt to make finite element model more realistic by taking time dependent nonlinear characteristics of material into consideration which happen in the site of the construction of the structures.

ACKNOWLEDGEMENTS

Authors would like to thank all the researcher scattered in all over the world, working hard to identify unseen effects on structural behavior of the building and presenting to the engineer communities for reducing the risk under any situation. Authors also express cordial gratefulness to the references for introducing and expressing this procedure in such an easy way.

REFERENCES

[1] Rosenboom O.A., Paret T.F.and Searer G.R.(2012), "Chronological Construction Sequence, Creep, Shrinkage and Pushover Analysis of an Iconic 1960s Reinforced Concrete Building", Proceedings 2012, 15th World Conference in Earthquake Engineering, Lisbon

[2] Irwin, Baker, Korista, Weismantle & Novak (2006), "The Burj Dubai Tower: Wind Tunnel Testing of Cladding and Pedestrian Level", Structure Magazine, published by NCSEA, November 2006, pp 47-50.

[3] William F. Baker, D. Stanton Korista and Lawrence C. Novak, "Engineering the World's Tallest – Burj Dubai", proceedings 2008, Council of Tall buildings and Urban Habitat 8th World Congress 2008, Dubai 1-10.

[4] Computers and Structures, Inc. (2009). CSI Analysis Reference Manual for SAP2000, ETABS, SAFE and CSiBridge, Berkeley, California.

[5] BNBC (2006) Bangladesh National Building Code, Housing and Building Research Institute, Mirpur, Dhaka, Bangladesh.

[6] Dinar, Y., Nazim U., R., and Das, P., "Variation of Deflection of Steel High-Rise Structure Due to P-Delta Effect considering Global Slenderness Ratio." International Journal of Emerging Technology and Advanced Engineering, Vol 3, Issue 12, December 2013, pp 250-256