ECE 523 Engineering Applications of Machine Learning and Data Analytics

Project Report

On

Predicting Alpha Parameter to Model Modal Behavior of the High-Rise Building

Submitted by: Sudan Pandey

May 2023

Civil & Architectural & Engineering Mechanics
The University of Arizona

Contents

List of Tables

List of Figures

Abstract

Seismic analysis of tall building has been the demanding job for many structural designers. Ensuring safety of the structures against earthquakes along with other loading is the main objective of the designer. The structural analysis for earthquakes is a continuous process of evolution. Procedures which are complex but more accurate to simple but less accurate are developed in this continuous evolution. Nonlinear response history analysis (NLRHA) is the most accurate procedure among other procedures. To overcome this limitation, a simplified procedure developed based on the uncoupled modal response history analysis (UMRHA) and coupled shear-flexural cantilever beam model (CSFCBM) can be utilized. The underlying assumption is that the UMRHA procedure can compute the nonlinear seismic responses mode by mode, where each vibration mode is assumed to behave as a single-degree-of-freedom system. The nonlinear seismic responses are approximately represented by the sum of the modal responses of a few vibration modes. However, UMRHA requires knowledge of the modal properties and modal hysteretic behaviors. Therefore, the CSFCBM can be employed to estimate the required modal properties and modal hysteretic behaviors. The inelastic seismic demands of the building can be determined using the UMRHA procedure with the computed modal properties obtained by CSFCBM. One of the important parameters for the CSFCBM model is the alpha parameter. An alpha parameter is a non-dimensional parameter and it can be obtained from structural modal analysis. However, in this study we want to predict the alpha parameter without doing any kind of finite element modeling.

This project will involve studying the ⁰ parameter of typical reinforced concrete high rise core wall buildings. The alpha parameters are obtained from the modal analysis of full 3D buildings of the case study buildings. Correlations between different building parameters are studied. It is found that the selected index parameter GA/EI is the best predictor of the α. Finally, a linear model based on GA/EI index is developed to predict α.

1. Introduction

Today, 4.2 billion which is 55% of the world's population lives in urban area and this is expected to increase to 68% by 2050 [1]. Asia is the home to 54% of the world's urban population [1]. Tall building is emerging as a popular choice among urban planners, driven by the increasing population combined with increasing cost of land and other factors [2], and will have an expanding role in the urban fabric [3]. High-rise reinforced concrete core-wall buildings are gaining popularity because they offer advantages of lower costs, faster construction, and more open and flexible architecture compared with high-rise buildings with other lateral force resisting systems [4]. They are also recently being built in high seismic areas [5]. In core wall structures, the lateral load resisting system consist of a central core walls, peripherals columns, and, in some cases, outriggers connecting between the core wall and the columns.

Seismic analysis of tall building has been the demanding job for many structural designer. Ensuring safety of the structures against earthquakes along with other loading is the main objective of the designer. The structural analysis for earthquake is a continuous process of evolution. Procedure which are complex but more accurate to simple but less accurate are developed in this continuous evolution. Nonlinear response history analysis (NLRHA) is a most accurate procedure among other procedure. However, for the complex system like tall buildings, performing NLRHA with many ground motions is a tedious job and requires a great expertise to acquire physical insight of NLRHA results in decision making. There are number of simpler procedures for seismic analysis like Nonlinear Static Pushover analysis (NSP), Modal Pushover Analysis (MPA) and Response Spectrum Analysis (RSA). NSP procedure is recommended by some guidelines and buildings design standards such as ATC-40 [6], FEMA-356 [7], and ASCE-41-06 [8], which consider the fundamental vibration mode only. However, it is not suitable for tall buildings which have the higher mode effects [9]. MPA is developed by Chopra and Goel [10] which consider all significant modes but this procedure also has errors coming from the assumed hysteretic behavior and modal combination [9]. The response spectrum analysis (RSA) procedure, which accounts for the multi-mode effects, is commonly used in the seismic design of high rise core wall buildings. However, recent studies have shown that this method significantly underestimates the inelastic seismic demands because all significant modes may not experience same level of nonlinearity [7]. Recently a different analysis procedure called Uncoupled Modal Response History Analysis (UMRHA) is studied by Mehmood et al [9]. This procedure was originally developed by Chopra and Goel [10]. It requires a very low computational effort comparing to NLRHA. This method provides more insight into the complex nonlinear seismic responses of the tall buildings and allows engineer to develop effective strategies to improve the seismic performance of these buildings. Therefore it is a convenient analysis procedure for seismic performance evaluation of tall buildings [9].

UMRHA procedure facilitates the computation of nonlinear seismic responses mode by mode, where each vibration mode is assumed to behave as a nonlinear single-degree-of freedom (SDOF) system. The nonlinear seismic responses are approximately represented by the sum of the modal responses of several vibration modes. The UMRHA procedure was applied to estimate the nonlinear seismic responses of several high-rise buildings with different heights, configurations, and arrangements of shear walls, and its accuracy was found to be satisfactory. By this method, the degrees of freedom could be reduced from several thousands (NLRHA) to just a few (UMRHA), and the computational effort and time were significantly reduced. However, the UMRHA procedure requires knowledge of the modal properties and modal hysteretic behavior. The modal parameters can be obtained from an eigen analysis and a cyclic modal pushover analysis (MPA) of a full 3D nonlinear FEM model, which a computationally expensive. To simplify this process recent study has been done by introducing CSFCBM to represent high-rise building. CSFCBM is one of the simplest models that can simulate the complex behavior of a wall frame structural system. This model can be used to estimate the required modal properties and modal hysteretic parameters without constructing a complete 3D nonlinear FEM. This will reduced the required building information to a bare minimum and facilitate the seismic analysis of the buildings even though the detailed information is not available. [11] The UMRHA procedure along with CSFCBM has been applied to analyze the buildings under different earthquakes and the accuracy has been found satisfactory. One of the important parameters for the CSFCBM model is the alpha parameter. An alpha parameter is a non-dimensional parameter and it can be obtained from structural modal analysis. However, in this study we want to predict the alpha parameter without doing any kind of finite element modeling.

This project will involve studying the alpha parameter of typical reinforced concrete high rise core wall buildings. The alpha parameters are obtained from the modal analysis of full 3D buildings of the case study buildings. First the correlation of alpha parameters with different building parameters are studied. It is found that the alpha has a strong positive correlation with the ratio of GA and EI, where GA is the shear rigidity of the primary shear walls and EI is the flexural rigidity of the primary shear wall. It is noted that the due to limited number of case study, significant correlation between other parameters with alpha wasn't seen. In the future study, the plan is to gather large number of building data to check the correlation with all different building parameters to have a better idea on the better predictor of alpha. In this study the ratio of GA and EI is used to predict the alpha parameter. This is just an to show that we can come off with some good predictor and train a model to predict alpha value.

1.1. UMRHA

UMRHA procedure can be visualized as an extension of Classical Modal Analysis procedure. In the Later, the complicated dynamic responses of an elastic multi-degree-of-freedom (MDF) system are represented by the summation of individual responses of many vibration modes. The response behavior of each vibration mode is fundamentally similar to linear SDF system, which is defined by few modal properties, making it simple to handle. Moreover, it is good enough to consider first few modes to accurately describe the complex linear structural responses in most of the cases. Basing classical modal analysis procedure, UMRHA procedure aims to widen the scope for inelastic limits. The theoretical basis for modal analysis remain valid only for linear system but it is still assumed that it is approximately valid for inelastic systems [10]. In UMRHA procedure, the behavior of each vibration mode is expressed by a nonlinear SDF system. The following expression shows the governing equation of the nonlinear SDF system.

$$\ddot{D}_i(t) + 2\xi_i\omega_i\dot{D}_i(t) + F_{si}(D_i, \dot{D}_i)/L_i = -\ddot{x}_g(t)$$

Here, L_i is given by $L_i = \Gamma_i M_i$ where, Γ_i is the modal participation factor and M_i is the modal mass of any i^{th} mode. ω_i and ξ_i are the natural frequency and the damping ratio of the i^{th} mode, respectively. $D_i(t)$ is the i^{th} mode response time history for input ground acceleration vector $\ddot{x}_g(t)$. More details about development of UMRHA procedure can be found in Chopra and Goel [12]. To solve (1), the restoring force function $F_{si}(D_i, \dot{D}_i)$need to be known. This describes the generalized force deformation relationship for i^{th} mode of a MDF system. The force deformation relationship depends on the key structural characteristics and type of lateral loading system and this may range from simple hysteretic behavior (e.g. bilinear, elastoplastic) to relatively detailed behaviors (e.g. stiffness and strength degrading system). For high rise buildings $F_{si}(D_i, \dot{D}_i)$ can be found by idealizing actual cyclic pushover curve with appropriate hysteretic modal. That is, the modal hysteretic behavior of a high rise RC shear wall building can be identified by the cyclic modal pushover analysis. Fig. 1 represents the basic concept of the UMRHA procedure.

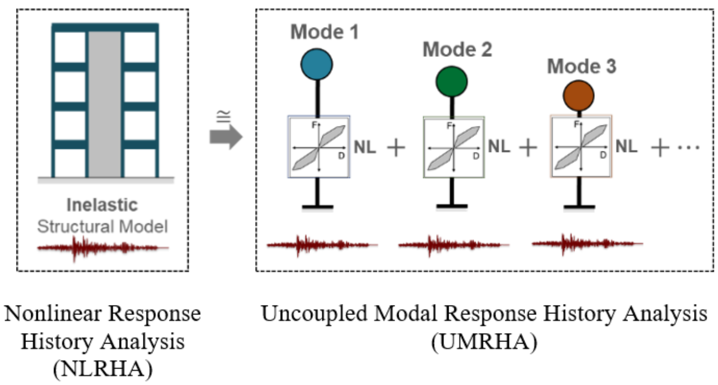

Figure 1: The basic concept of Uncoupled Modal Response History Analysis (UMRHA) [12]

1.2. CSFCBM

Figure 2 below shows the CSFCBM as an approximate model of a high rise building with a frame wall system. It may not be applicable to other structural systems (e.g., outrigger and belt truss). The model comprises a vertical cantilever flexural beam connected to a vertical cantilever shear beam by numerous axially rigid links that transmit only horizontal forces. Owing to this arrangement, the lateral deflections of the two beams remain identical when a lateral load is applied. The flexural beam represents the combined effects of RC walls and other structural components that deform in the flexural mode, whereas the shear beam represents the combined effects of frames and other structural components that deform in the shear mode. The links represent the slabs that horizontally connect RC walls and frames; the links are treated as rigid members because of the extremely high in plane stiffness of the slabs.

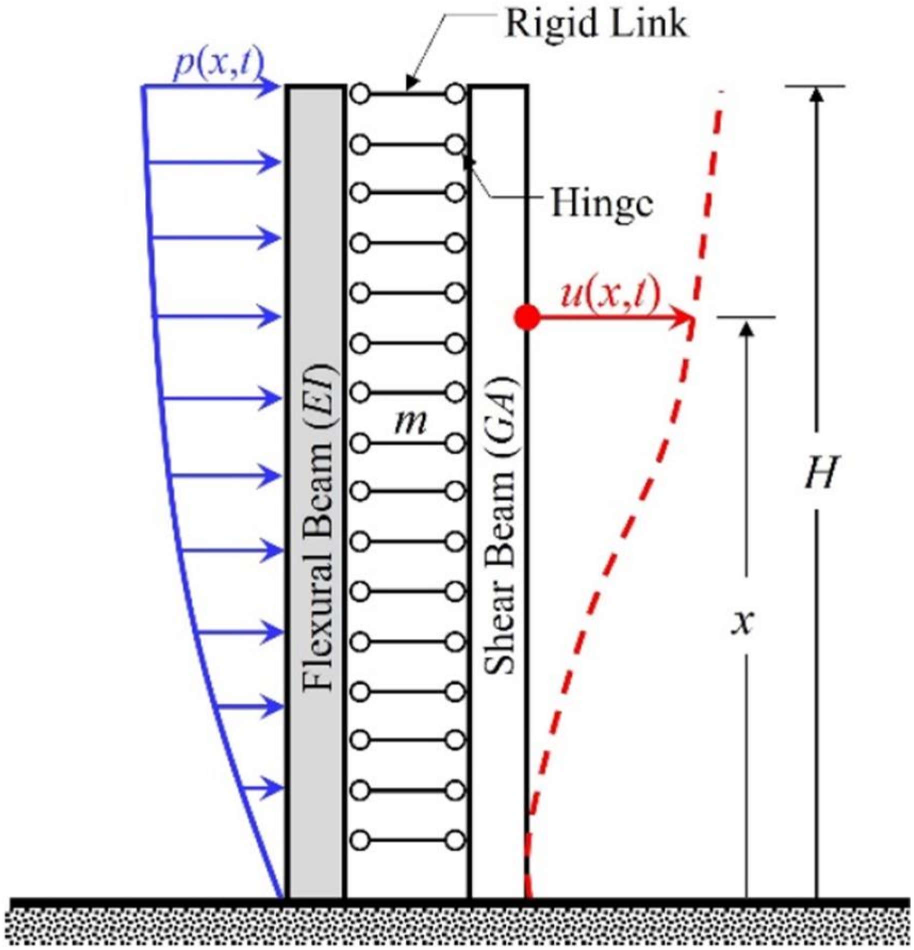

Figure 2: Definitions and Properties of CSFCBM [11]

The detailed of the CSFCBM can be found in Suwansaya 2023 [11]. In his study we can see that the alpha (α) parameter is instrumental in determining the modal characteristics of a building. Fo example, the flexural action dominates when α is low and the shear action dominates when α is high. Once α is is specified, the eigenvalue parameter (γ_i) can be determined using the characteristic equation, and the corresponding mode shape ($\emptyset_i$)), modal frequency (w_i)), and natural period (T_i) can be obtained ($T_i = 2\pi/w_i$).
Figure 3 shows the effect of α on the period ratios. The a values of typical buildings are likely to be somewhere between these two extremes, namely, ideal flexural and shear beams. Their a values typically fall into zone B (1 < α < 10), where the period ratios vary significantly with the change in a. This suggests that one could easily identify the a value of a given building by simply checking its period ratios.
To represent a high-rise building using CSFCBM, one needs to determine the model parameters, namely, H, M, EI, and GA. Among these, height H is a basic building parameter that can be obtained easily. The mass per unit height m can also be estimated conveniently if the detailed drawings of the building are available. Otherwise, m can be approximately estimated from the gross mass density (ρ_b) of buildings in the same class. The gross mass density is defined as the total building mass divided by the total encased volume of the building. The gross mass density of RC buildings, for example, typically varies from 250 to 350 kg/m3. However, the remaining two parameters, EI and GA, are difficult to evaluate directly despite the availability of detailed drawings [11].

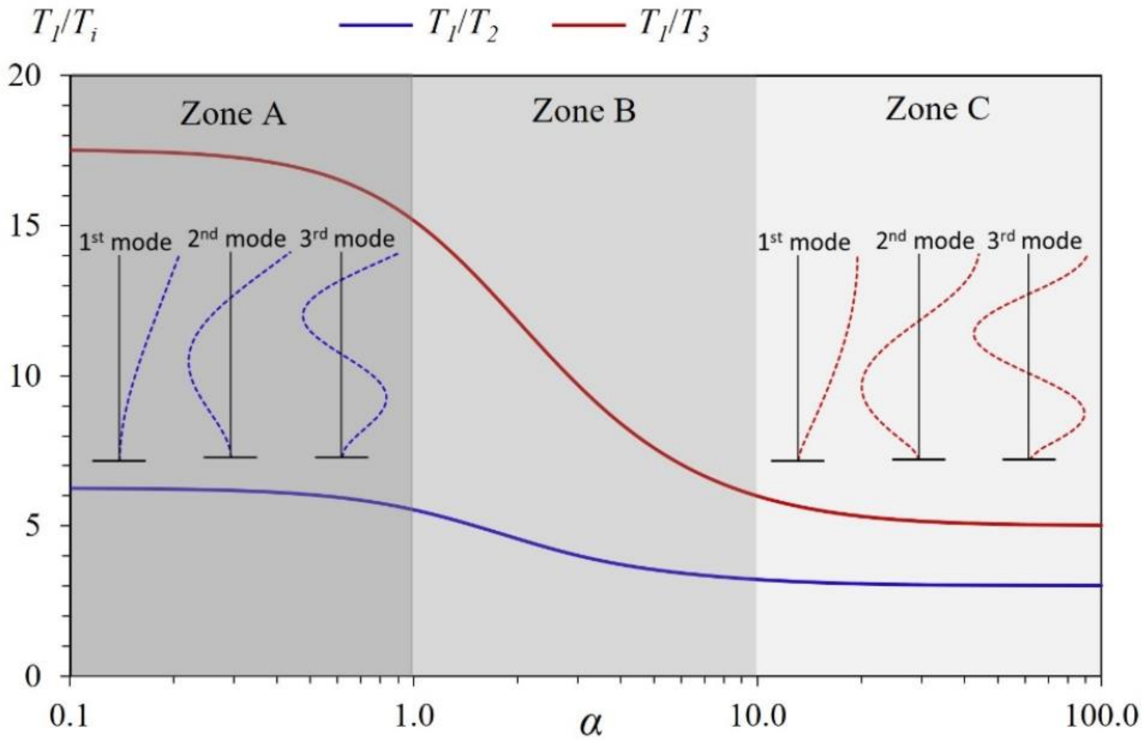

Figure 3: Effect of α on the period ratios of CSFCBM [11]

1.3. Case Study Buildings

The four high-rise buildings chosen for the case study had heights ranging from 19 to 45 stories and were located in Bangkok, Thailand. They were used as reference cases to verify the accuracy of CSFCBM in estimating the building modal properties and evaluating the building seismic responses. These buildings were named S1, B1, B2, and B3, and their typical floor plans and 3D views are depicted in Figure 4. In every building, the gravity-load-carrying and lateral-load-resisting components were RC slab-column frames (gray and blue regions) and RC walls or cores (red regions), respectively. Masonry infill walls (black dashed lines) were broadly used as exterior and interior partition walls. In all cases, the foundation structure was a mat foundation lying on piles. Buildings B1, B2, and B3 had podiums, and B1 had an unsymmetrical arrangement of RC walls in its tower floor plan; these are vertical and plan irregularities commonly found in high-rise buildings. Conversely, building S1 was a regular building with a symmetrical arrangement of RC walls and uniform structural properties along its height from the base to the top. Table 1 lists the key properties and characteristics of these buildings.

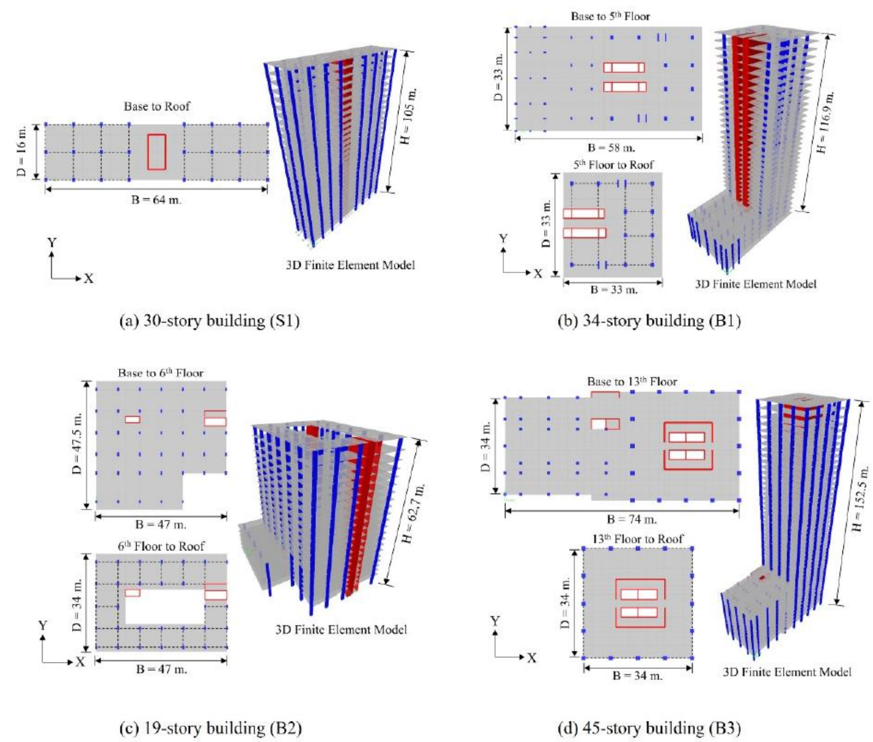

Figure 4: Typical floor plans and 3D views of the four case study buildings

Table 1: Salient properties of four case study buildings

Building Name		S1	B1	B2	B3
Width of the tower, B (m)		64.0	31.0	47.0	33.6
Depth of the tower, D (m)		16.0	32.5	34.0	33.6
Height, H (m)		105.0	116.9	59.5	152.5
No. of stories		30	34	19	45
Typical story height, h (m)		3.5	3.2	2.9	3.5
RC wall section area/footprint area (%)		0.88	1.62	0.54	2.42
RC column section area/footprint area (%)		2.81	1.45	1.06	2.04
RC typical wall thickness (m)	Base–10th floor	0.35	0.25	0.25	0.45
	10th–20th floor	0.35	0.25	0.25	0.40
	20th floor–roof	0.35	0.25	0.25	0.35
RC column typical dimension (m)	Base–10th floor	1.0 × 1.2	0.9 × 1.2	0.5 × 1.2	1.2 × 1.2
	10th–20th floor	1.0 × 1.2	0.9 × 1.2	0.5 × 1.2	1.2 × 1.2
	20th floor–roof	1.0 × 1.2	0.9 × 1.2	0.5 × 1.2	1.2 × 1.2
Longitudinal reinforcement ratio in RC wall (%)	Base–10th floor	4.0	1.27	2.27	2.95
	10th–20th floor	4.0	0.81	1.45	1.44
	20th floor–roof	4.0	0.46	0.93	1.44
Specified compressive strength of concrete, $f_c{}'$ (MPa)	RC walls	45	45	42	45
	RC column	45	32	42	40
	RC and PT slabs *	32	32	32	32
Specified yield strength of longitudinal reinforcement steel bar, f_y (MPa)		490	390	390	390

* PT slabs = post-tensioned concrete slabs.

Perform 3D version was used to create nonlinear FEMs of the four buildings. The models were utilized to determine the buildings' modal hysteretic behavior using cyclic MPA and to compute their nonlinear seismic responses. Linearized versions of these models (linear FEMs) were used to determine the modal properties of these buildings. Details of the FEM models can be found in Pandey et. al. [12] and Suwansaya et. Al. [11]. The modal analysis was performed. Based on the period ratios of different modes, α value is calculated for each building.

Table 2 shows the α value for all three buildings. Furthermore, an index, a ratio of GA and EI was calculated for each building. This index is calculated assuming this will be a strong predictor of α. At the same time, the building information required for calculating this index should be minimal as possible and the calculations procedure is simple and practical. Table 2 also shows the index GA/EI on the last row.

Table 2: α parameters of four case study buildings [11]

Building Name	X Direction				Y Direction			
	S1	B1	B2	B3	S1	B1	B2	B3
Height of the building, H (m)	105.0	116.9	59.5	152.5	105.0	116.9	59.5	152.5
First mode period, T_1 (s)	4.420	3.112	1.704	2.717	3.371	5.487	2.701	2.854
Second mode period, T_2 (s)	1.088	0.613	0.410	0.574	0.744	1.457	0.800	0.564
T_1/T_2	4.063	5.077	4.156	4.733	4.531	3.766	3.376	5.060
α	2.88	1.43	2.68	1.80	2.06	3.76	6.58	1.45
EI_o ($\times 10^{12}$ N·m^2)	1.32	9.96	1.35	25.2	3.75	0.88	0.34	20.6
GA_o ($\times 10^{10}$ N)	7.05	2.38	1.28	8.67	10.2	9.56	6.92	8.67
$\sqrt{GA_o/EI_o}$ (1/m)	0.232	0.049	0.098	0.059	0.164	0.329	0.453	0.065

Based on the available building data, the building parameters used in this study are summarized in the table below.

Table 3: Building parameters used for this study

Building	α	H	L	W	Wall area %	Col. area %	Wall thick	Rebar %	fc	GA	EI	GAo/EIo
S1	2.88	105	64	16	0.88	2.81	0.35	4	45	1.32	7.05	0.232
B1	1.43	116.9	31	32.5	1.62	1.45	0.25	1.27	45	9.96	2.38	0.049
B2	2.68	59.5	47	34	0.54	1.06	0.25	2.27	42	1.35	1.28	0.098
B3	1.8	152.5	33.6	33.6	2.42	2.04	0.45	2.95	45	25.2	8.67	0.059
S1	2.06	105	16	64	0.88	2.81	0.4	2.085	43.5	3.75	10.2	0.164
B1	3.76	116.9	32.5	31	1.62	1.45	0.43	1.87	43.2	0.88	9.56	0.329
B2	6.58	59.5	34	47	0.54	1.06	0.46	1.655	42.9	0.34	6.92	0.453
B3	1.45	152.5	33.6	33.6	2.42	2.04	0.49	1.44	42.6	20.6	8.67	0.065

2. Methodology and Model Design

2.1. Correlation of the parameters

The correlation coefficient r is a unit-free value between -1 and 1. Statistical significance is indicated with a p-value. Therefore, correlations are typically written with two key numbers: r and p. The closer r is to zero, the weaker the linear relationship. Positive r values indicate a positive correlation, whereas the values of both variables tend to increase together. Negative r values indicate a negative correlation, where the values of one variable tend to increase when the values of the other variable decrease. The values 1 and -1 both represent “perfect” correlations, positive and negative respectively. Two perfectly correlated variables change together at a fixed rate. We say they have a linear relationship; when plotted on a scatterplot, all data points can be connected with a straight line.

2.2. Machine Learning Approaches

Training and Test Data:

The data set was divided into the training and test set in the 80/20 proportion. The model was created using the training set and finally tested on the test set. This helped us to report the robustness of the model.

Models and Classifications:

Based on the correlation plot and scatter plot, we saw the linear relationship between selected index (GA/EI) and α, hence Linear model is used to train and test the model.

i) Linear Model:

The effect of an index on α was assessed using the linear model (ordinary least square regression). Ordinary Least Square Regression (OLS) is a common technique for estimating coefficients of linear regression equations which describe the relationship between one or more independent quantitative variables and a dependent variable. Maximum likelihood and Generalized method of moments estimator are alternative approached to OLS.

The model specification for the linear model-

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_1 + \ldots\ldots\ldots\ldots + \beta_k X_1 + \upsilon$$

Where, Y is the α as a continuous dependent variable; βo is the intercept; β_1,.... β_k are the coefficients; X_1, X_2.... X_k are the features that include GA/EI, H, W, B etc.; υ is the error term. But in this model, only GA/EI will be used as a predictor of the α. Hence the above equation reduced to,

$$Y = \beta_0 + \beta_1 \alpha + \upsilon$$

3. Result and Analysis.

3.1. Correlation of the parameters

Figure 5 shows the scatter plots between all the selected parameters. Based on the scatterplots it is seen there is a strong negative relationship with alpha between height, rebar percent in the wall, rebar in the column, wall thickness, and compressive strength of the concrete. We can also see the linear correlation between GA/EI and α. Figure 6 shows the correlation matrix between all the parameters. R value of 0.94 between α and GA/EI index shows the strong positive correlation between them.

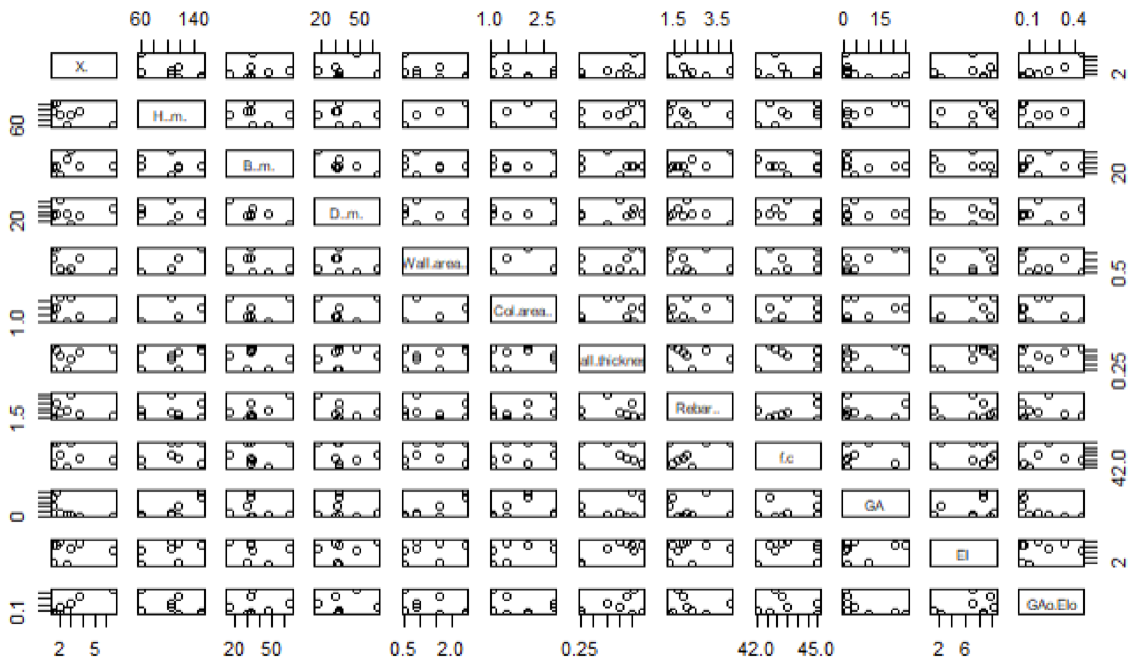

Figure 5: Scatter plot of all the parameters

	X.	H..m.	B..m.	D..m.	Wall.area..	Col.area..	Wall.thickness	Rebar..	f.c	GA	EI	GAo.EIo
X.	1.00000000	-0.66732052	0.10310823	0.15019386	-0.5706092	-0.45064704	0.27536208	-0.05609826	-0.32245788	-0.58933392	0.07392837	0.94071622
H..m.	-0.66732052	1.00000000	-0.21705880	-0.21705880	0.9426564	0.45991951	0.41987777	0.02837631	0.44944454	0.82195037	0.49022874	-0.53892659
B..m.	0.10310823	-0.21705880	1.00000000	-0.82532652	-0.2459776	0.04503572	-0.30897208	0.68909675	0.15613933	-0.22581482	-0.36900120	0.07144011
D..m.	0.15019386	-0.21705880	-0.82532652	1.00000000	-0.2459776	0.04503572	0.22626381	-0.46077127	-0.33652709	-0.10335830	0.29576846	0.13640867
Wall.area..	-0.57060924	0.94265639	-0.24597758	-0.24597758	1.0000000	0.14904165	0.42727157	-0.15541028	0.29920788	0.88854206	0.34737903	-0.52668886
Col.area..	-0.45064704	0.45991951	0.04503572	0.04503572	0.1490417	1.00000000	0.20970619	0.56137778	0.46328455	0.17601297	0.56138585	-0.23171867
Wall.thickness	0.27536208	0.41987777	-0.30897208	0.22626381	0.4272716	0.20970619	1.00000000	-0.06029948	-0.13795635	0.36680876	0.85240848	0.35366237
Rebar..	-0.05609826	0.02837631	0.68909675	-0.46077127	-0.1554103	0.56137778	-0.06029948	1.00000000	0.45561181	-0.06435331	0.13424287	0.01110902
f.c	-0.32245788	0.44944454	0.15613933	-0.33652709	0.2992079	0.46328455	-0.13795635	0.45561181	1.00000000	0.29317380	0.07926892	-0.22934313
GA	-0.58933392	0.82195037	-0.22581482	-0.10335830	0.8885421	0.17601297	0.36680876	-0.06435331	0.29317380	1.00000000	0.20769485	-0.66012806
EI	0.07392837	0.49022874	-0.36900120	0.29576846	0.3473790	0.56138585	0.85240848	0.13424287	0.07926892	0.20769485	1.00000000	0.29211758
GAo.EIo	0.94071622	-0.53892659	0.07144011	0.13640867	-0.5266889	-0.23171867	0.35366237	0.01110902	-0.22934313	-0.66012806	0.29211758	1.00000000

Figure 6: Correlation Matrix of the parameters

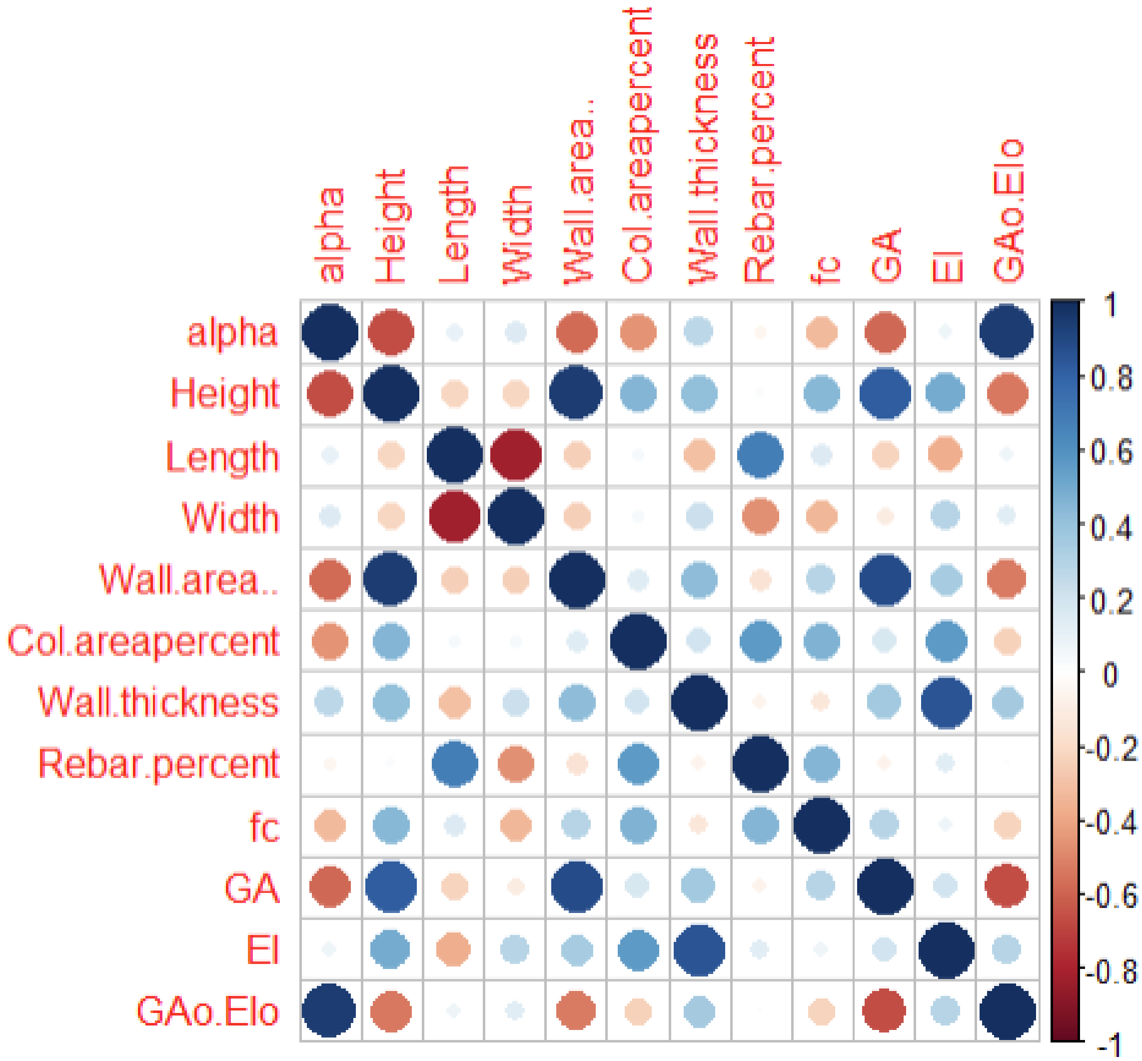

Figure 7: Correlation Matrix of the parameters

Figure 7 shows the heat map of correlation between all the parameters. It is clear from the scatter plot and correlation matrix, GA/EI index is the better predictor based on this limited data. Our aim is to gather more data on the buildings and their properties to find the other significant parameter. It might be possible to find a better predictor of theα. For this study, we will use GA/EI to predict the α.

3.2. Test data

Just to show the linear regression learning model, the GA/EI and α data are collected for 20 buildings and more data are generated based on the empirical relationship and adding some noises. It should be noted that this will make our model fit all the training data linearly. The training data are plotted and shown in Figure 8. The linear regression model was done in R, the error of the linear model is shown in Table 4. Figure 9 shows the linear fitting of the data through the model.

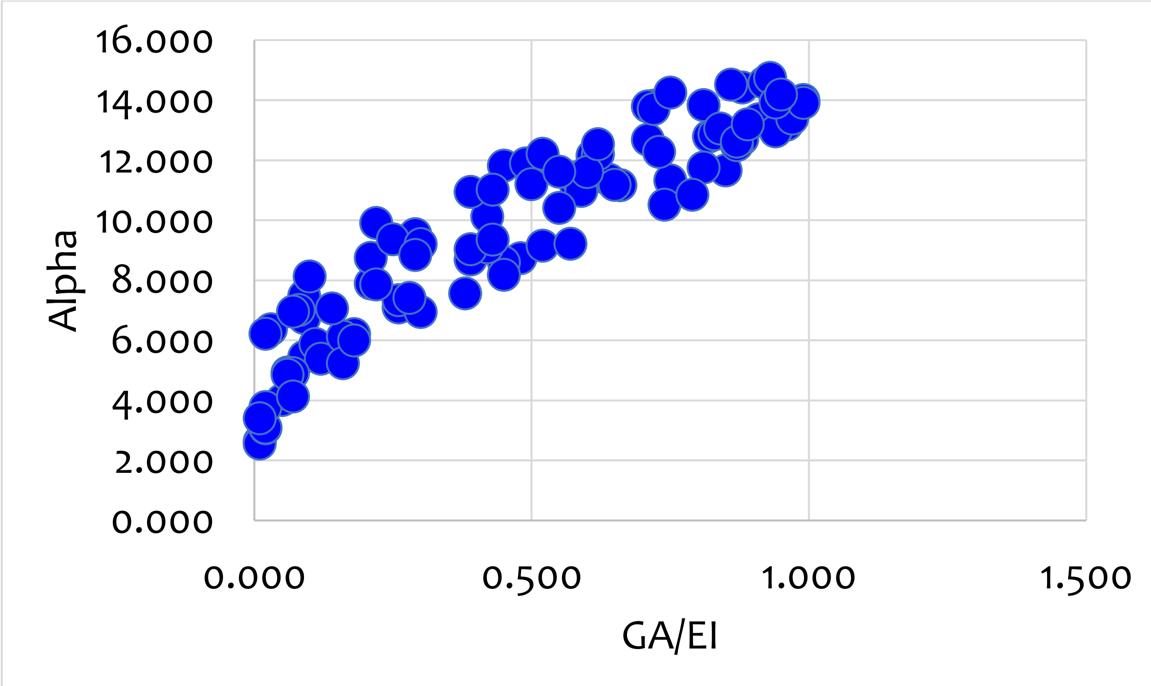

Figure 8: Training and Test Data

Table 4: Error of the linear model

Error		
RMSE	Rsquared	MAE
0.3884914	0.8269071	0.3268007

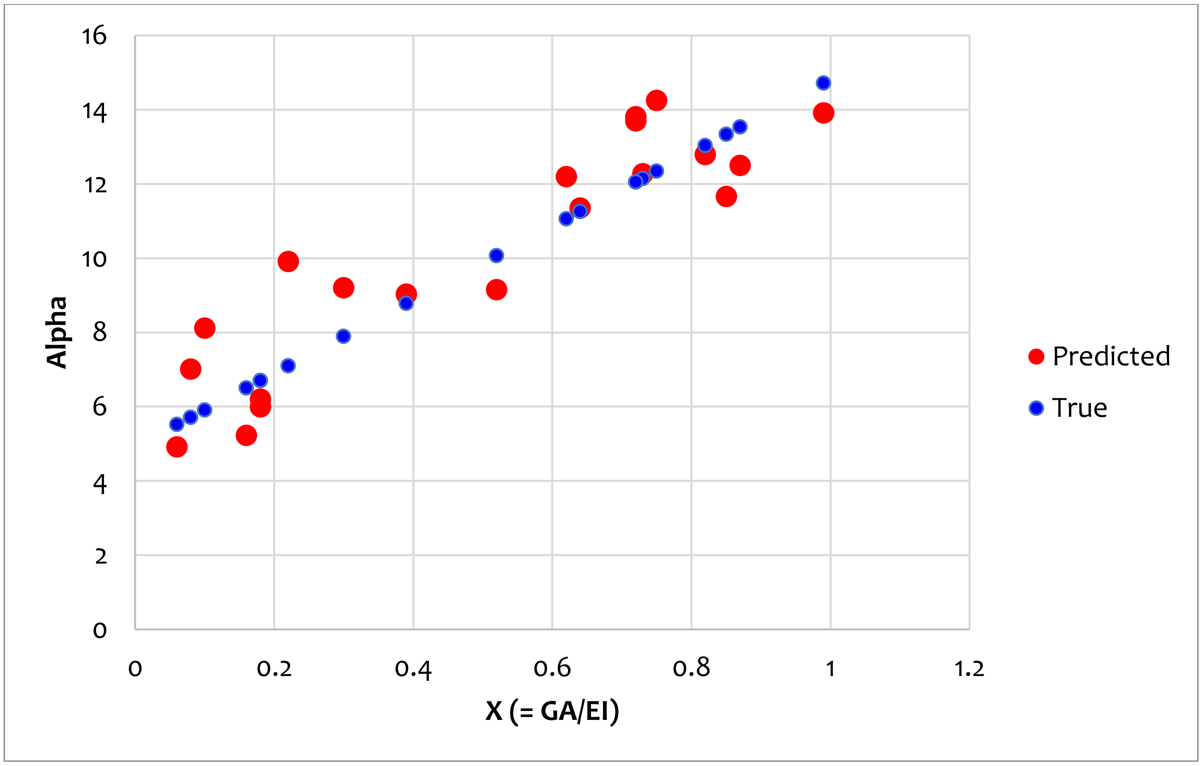

Figure 9: True vs Predicted α for the test data.

4. CONCLUSION

Based on the above study following conclusions are made:

1. There is a strong linear relationship between the selected index GA/EI and α
2. We need more buildings data to find other predictors of the α.
3. Our ultimate aim is to not use GA/EI to predict the alpha value but to use readily available building information.

5. REFERENCES

[1] United Nations https://esa.un.org/unpd/wup/

[2] Heller, J., Manus, C., and Nikitas, C. (2008). San Francisco: Promoting tall buildings through sustainable incentives, Proc. Of the 8th CTBUH World Cong. On Tall & Green: Typology for a Sustainable Urban Future, pp. 373-379

[3] Kheir Al-Kodmany. "The Logic of Vertical Density: Tall Buildings in the 21st Century City" International Journal of High-Rise Buildings Vol 1, No 2, June 2012, 131-148.

[4] Maffei, Joe, and Noelle Yuen. "Seismic performance and design requirements for high-rise buildings." Structure Magazine (2007): 28-32.

[5] Moehle, Jack P. "Performance-based seismic design of tall buildings in the US." 14th World Conference on Earthquake Engineering (CD), Beijing, China. 2008.

[6] Applied Technology Council. Seismic Evaluation and Retrofit of Concrete Buildings, Report ATC-40, Novemeber 1996.

[7] FEMA 356. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency Washington.

[8] ASCE/SEI 41-06. (2007). Seismic Rehabilitation of Existing Buildings. American Society of Civil Engineers Virginia

[9] Mehmood, Tahir, Pennung Warnitchai, and Phichaya Suwansaya. "Seismic Evaluation of Tall Buildings Using a Simplified but Accurate Analysis Procedure." Journal of Earthquake Engineering 22.3 (2018): 356-381.

[10] Chopra, Anil K., and Rakesh K. Goel. "A modal pushover analysis procedure for estimating seismic demands for buildings." Earthquake engineering & structural dynamics 31.3 (2002): 561-582.

[11] Suwansaya P, Warnitchai P. Simplified Procedure for Rapidly Estimating Inelastic Responses of Numerous High-Rise Buildings with Reinforced Concrete Shear Walls. Buildings. 2023; 13(3):670. https://doi.org/10.3390/buildings13030670

[12] Pandey, S.; Warnitchai, P.; Vasanthapragash, N.; Najam, F. Development of modal hysteretic model for the seismic response analysis of tall buildings with RC shear wall. In Proceedings of the 7th Asia Conference on Earthquake Engineering, Bangkok, Thailand, 22–25 November 2018.

[13] Pandey, S. Development of Modal Hysteretic Model for the Seismic Response Analysis of Tall Buildings with RC Shear Wall. Master's Thesis, Department of Civil and Infrastructure Engineering. Asian Institute of Technology, Pathum Thani, Thailand, 2017.