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# MATHEMATICAL MODELLING OF FORCE-DISPLACEMENT IN HIGH-RISE FRAME STRUCTURE

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***Abstract:*** *Mathematical modelling of force-displacement in high-rise frame structure was carried out to examine the most common structural systems that are used for reinforced concrete (RC), under the action of gravity and wind loads, these treatments may lead to erroneous wind loading predictions for structural design. Measured pressures are typically used for the structural design without the calibration in the engineering practice. Therefore, a rigid frame was used as the structure. The behavior of the frame under different wind load condition, was modelled and studied. In this study, a 15 stories of RC frame structure was analysed and designed with the changing of minimum wind pressure to 1kN/m, 2kN/m, 3kN/m, 4kN/m, and 5kN/m that produce wind load forces at each story starting from 3-15 storeys. A total number of 65 sample variables of displacement values from each respectively test were obtained (i.e. storeys displacement results). ANOVA was carried out on the data obtained and the regression model was developed as F = 2.430 - 0.2621 FL + 0.08460 DX, from Minitab i.e. the independent variable "F" and the dependent variables "FL" and "DX" which defines the forces(F), Floor height (FL) and Storey displacement (DX) respectively. The study recommended developing a comprehensive understanding of the structural behavior of the frame before attempting to model it and utilize advanced mathematical modelling techniques such as finite element analysis as it is difficult to accurately predict the behavior of such structure due to the complexity of the structure and the number of variables involved. Additionally, the accuracy of the data used to create the model, can be difficult to obtain. The R-squared was obtained as 86.21% and P-value is 0, which shows a good fit and significance of data obtained from the force-displacement Analysis.*

***Index Terms:*** **Mathematical modelling, Force-displacement, Frame structure, Regression model, ProtaStructure.**

## I. INTRODUCTION

Mathematical modelling, in which researchers use mathematics to explain or interpret physical, social, or scientific phenomena, is an essential component of research. The Common Core State Standards for Mathematics (CCSSM) classify modeling as a K–12 standard for mathematical practice and as a conceptual category for high school (CCSSI, 2010). CCSSM also describes mathematical modelling as “the process of choosing and using appropriate mathematics and statistics to analyze empirical situations, to understand them better, and to improve decisions” Cortez and Anhalt, (2015). According to Ronald, (2010), the behavior of a structure is defined by the displacements and forces produced within the structure as a result of external influences. In general, structural theory consists of the essential concepts and methods for determining these effects. The process of determining them is known as structural analysis. Measured pressures are typically used for the structural design without the calibration in the engineering practice, these treatments may lead to erroneous wind loading predictions for the structural design. This study considered rigid frame structure to study the behavior of reinforced concrete frame under different wind load condition, and developing a mathematical model for the selected parameters. 15 stories of high rise building structure are used to analyze the behavior of the frame. ProtaStructures and Minitab programs were used for the structural analysis and mathematical modelling respectively. According to the Huppatz, (2015), Engineers are interested in designing devices and processes and systems that is, beyond observing how the world works, engineers are interested in creating artifacts that have not yet come to life. As noted by Herbert (In the Sciences of the Artificial), “Design is the distinguishing activity of engineering.” Thus, engineers must be able to describe and analyze objects and devices into order to predict their behavior to see if that behavior is what the engineers want. In short, engineers need to model devices and processes if they are going to design those devices and processes. The use of mathematics in solving real-world problems is often referred to as 'Mathematical modelling'. We could define this as the process of describing a real-world situation using mathematics. However, it must be done in such a way that it helps in the solution of the given problem.

## 2. LITERATURE REVIEW

### 2.1 GENERAL ON TALL BUILDINGS

(Renuka, and Kumar, 2015) High-rise structures have certain features. The structures are high & lead to higher vertical loads and higher lateral loads in comparison with lower buildings. Buildings between 75 feet and 491 feet (23 m to 150 m) high are the materials used for the structural system of high-rise buildings are reinforced concrete and steel. Vertical loads on the high rise structures have Dead loads arise from the weigh to the individual construction elements and the finishing loads and Live loads are dependent on use depending on the number of stories, live loads can be reduced for load transfer and the dimensioning of vertical load-bearing elements. Horizontal Loads Calculation of lateral loads should be carefully scrutinized. It generally arises from unexpected deflections, wind and earthquake loads Unexpected Deflections arises from imprecision in the manufacture of construction elements and larger components, another cause is the uneven settling of the foundation at an in-homogeneous site. Wind loads High-rise buildings are susceptible to oscillation. It should not be viewed as statically equivalent loads, but must be investigated under the aspect of sway behavior. Wind tunnel experiments are used to see the influence of the building shape on the wind load. The ability of wind loads to bring a building to sway must also be kept in mind. This oscillation leads both to a perceptible lateral acceleration for occupants, and to a maximum lateral deflection.

### 2.2 ELEMENTS OF MODELLlING

Cortez and Anhalt, (2015) Understanding the elements that modelling problems contain promotes modelling as a mathematical practice. The modelling process depicted in figure 1 is adapted from CCSSM. The elements, necessarily in this order, make up the six stages of the modelling cycle. The arrows in the diagram indicate the general path from beginning to end. After stage 5, “Validate conclusions,” a decision must be made as to whether the model will need improvement; this decision determines whether answer is reported or cycle back to formulating a new or modified model (stage 2). Navigating through the modeling cycle may also include revisiting a past stage, such as correcting computations (stage 3) during the interpretation of solutions (stage 4), although this is not explicitly shown in the diagram. The value in the modelling activity is a combination of the problem itself and the way it is managed in the classroom by allowing the students to recognize the modeling elements in their own work. Table 1 provides an explicit description of the work that is connected to each element of the modelling cycle. One hallmark of mathematical modelling is the decision making process that students/researchers go through when formulating a model. Making assumptions is particularly important because it requires one to take assertive measures with confidence that their decisions will help them develop a reasonable model. It is important to distinguish between assumptions, which affect the model directly, and procedural choices (such as conducting the computations in units of inches versus centimeters), which are necessary but do not define the model. During the process of making assumptions, it is helpful to engage in the discussion about the effect of their assumptions and justification of their choices (Anhalt, 2014). Consider the following example of a modelling problem, including how the elements of the cycle present themselves within the solution.

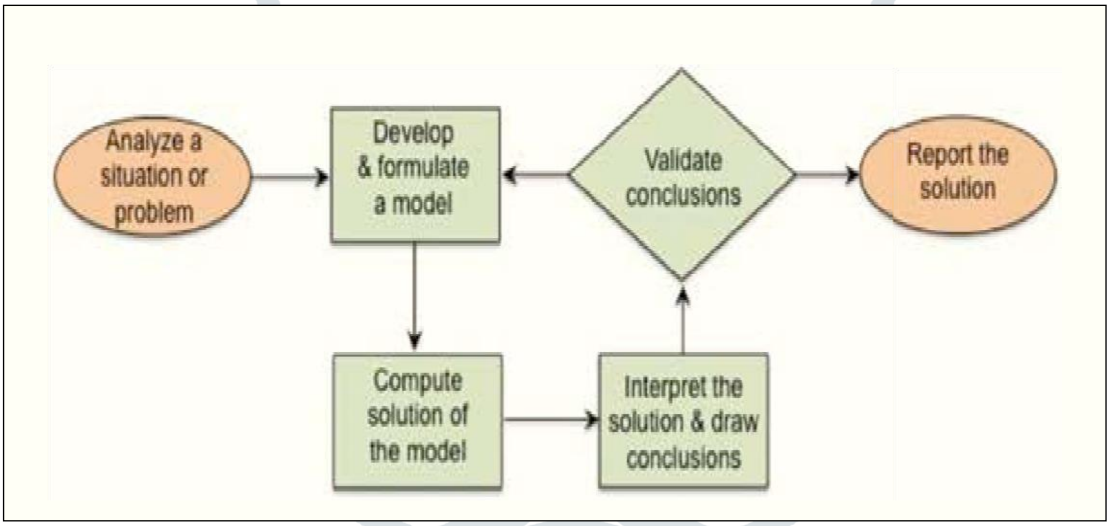


Figure 1: Element titles within the Modeling Cycle (CCSSI, 2010).

### 2.3 MATHEMATICAL MODELLING

(Azariy, and Yana, 2019) Mathematical model for assessing the high-rise apartment buildings complex quality. In modern conditions, the most important thing is to consider the problems of providing quality systemically. In this approach to the labor results, the following stages are distinguished: the transfer of the process quality to the quality of the labor result, the consideration of the quality of the product creation process, as a complex of sequential operations, which together form its quality. For this purpose the method of generalized (integral) evaluation is ideally suited, which is the basis of such science as "qualimetry", the founder of which was Professor G. G. Azgaldov, and J. Van Ettinger and George Setting. Worked on the development of this science abroad. The absence of complex indicators and criteria for assessing the progressiveness is the most significant methodological short of the methods used in construction. The use of a mathematical model that ultimately reflects the essence of considering phenomenon is the optimal solution for successful prediction and assessment of the factors influence on the complex quality index potential.

### 2.4 FORCE-DISPLACEMENT

Aryan *et al*., (2020) Selection of Optimum Structural System in the Design of Reinforced Concrete High-Rise Building under the effect of Seismic Load. Based on the analytic studies, Lateral displacement is directly proportional to the lateral stiffness and induced lateral force on the building. Absence of displacement prohibits the energy to be dissipated, and when the displacement is over the limit, the probability of structural damage and collapse is more. Comparing with model M-1, the model M-5 has the minimum storey lateral displacement, (55.16%) for the shear wall system, and the model M-8 has the minimum percentage of storey lateral displacement (60.18%) for the bracing system. Among both models, the model M-5 has the least lateral displacement percentage, in which the displacement is controlled by shear wall due to its proper position and increased mass and in-plane stiffness.

### 2.5 LATERAL WIND LOAD

(Shruti and Suresh, 2014) A Study on Behavior of Structural Systems for Tall Buildings Subjected to Lateral Loads, Based on the limited Study Carried Out, found out that; under the effect of wind loads, as the height of the structure increases, the lateral deflection and the overturning moment at the base increase. Tall buildings almost always require additional structural material, in order to limit the lateral deflection and resist the overturning moment, over and above that required for gravity loads only. Secondly, that the key idea in limiting the wind drift in a tall building is by changing the structural form of the building into something more rigid and stable to confine the deformation and increase stability. Thirdly, that the stiffness (rigidity) and stability requirements become more important as the height of the structure increases, and they are often the dominant factors in the design. Again that the building height increases time period has increased i.e., 45% to 50% increase can be observed from the graphs for every addition of 15 stories. More also that the Maximum base shear at the base of the building increase with the increase in number of stories. Hence it can be concluded that base shear depends mainly on seismic weight of the building. Finally, the reduction in the displacement of rigid frame with shear wall framed structure is 50 % with respect to RC frame Structure, 25% in case of shear walls and 60 % when outrigger was used. The main conclusions of this comparative study, concerning the efficiency of the presented five structural systems and the ability of each system in limiting the wind drift for a certain building height, can be summarized in the following: Rigid frame system the relatively high lateral flexibility calls for uneconomically large members. It is not possible to accommodate the required depth of beams within the normal ceiling space in tall rigid frame. Not stiff as other three systems and considered more ductile and more susceptible to wind failures. Rigid frame with shear wall the benefits of this system depend on the horizontal interaction, which is governed by the relative stiffness of walls and frames and the height of the structure. As the structure height and the stiffness of the frames increase, the interaction between walls and frames increases. The major factor in determining the influence of the frames on the lateral stiffness of this system is the height. As the structure height increases, the sharing of walls from the base shear decreases with respect to frames and more interaction induced between both of them.

## 3. OBJECTIVES OF THE PROJECT

1. To develop 3D Model of RC frame building structure
2. To analyze and design the structures with wind effect (from storey 3 up to 15) and various additional wind loading.
3. To obtained the displacement- values of the selected storeys of the building.
4. To generate the Mathematical model (Regression equation) for various parameter considered.

## 4. SCOPE AND LIMITATION

1. RC Frame structure.
2. Displacement due to following loading conditions only (Dead load (selfweight inclusive), live and Wind loads).
3. Displacement in the X-Direction (DX).
4. Analysis and design as per BS8110:1997 and BS6399.
5. Regression analysis (Minitab).

## 5. RESEARCH METHODOLOGY

To achieve the objectives of the study, that is to analyze and design the RC residential frame building using ProtaStructures and regression analysis in Minitab, the following methodology was adopted.

**Table 5.1: Structural details and inputs**

| Name | Details | Name | Details |
|---|---|---|---|
| Plan Dimension | 24m × 20m | Grade of concrete | M20/25 |
| Number of stories | 15 | Poisson ratio | 0.2 |
| Floor height | 3m | Slab thickness | 150mm |
| Size of beam-1 | 230mm × 450mm | Soil type | II-Medium |
| Size of beam-2 | 250mm × 450mm | Density of concrete | 25kN/m |
| Size of colmn-1 | 600mm × 600mm | Floor finishes | 1Kn/m |
| Size of colmn-2 | 600mm × 450mm | | |
| Size of column-3 | 450mm × 450mm | Live load | 3kN/m |
| Thickness of exterior wall | 250mm | Roof load | 1.5kN/m |
| Wall load | 12kN/m | Type of building | Residential |

## 5.2 SUMMARY PROCEDURE:

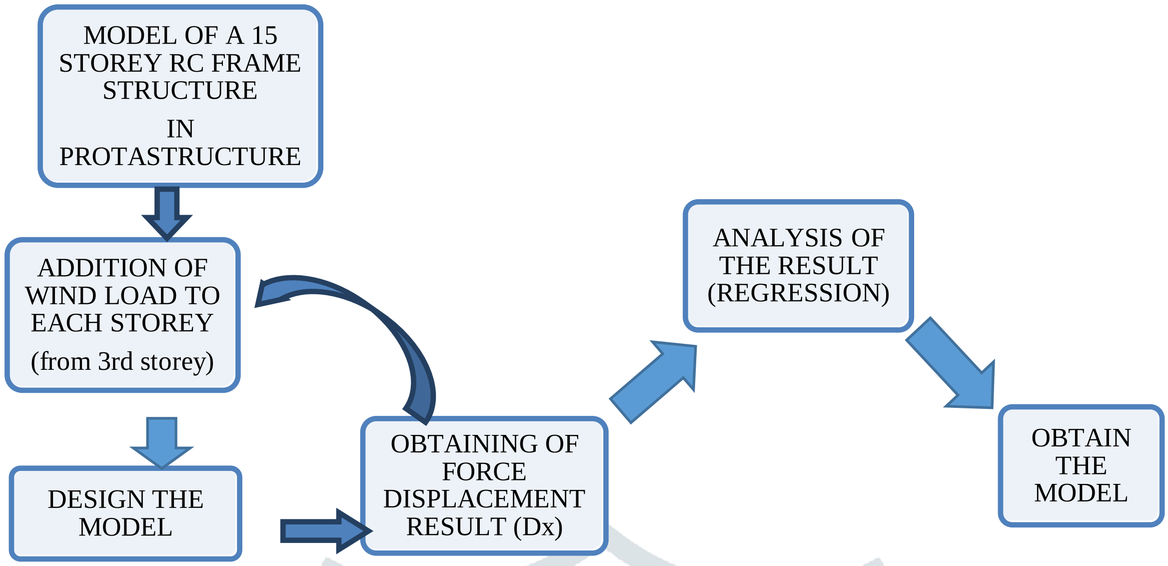


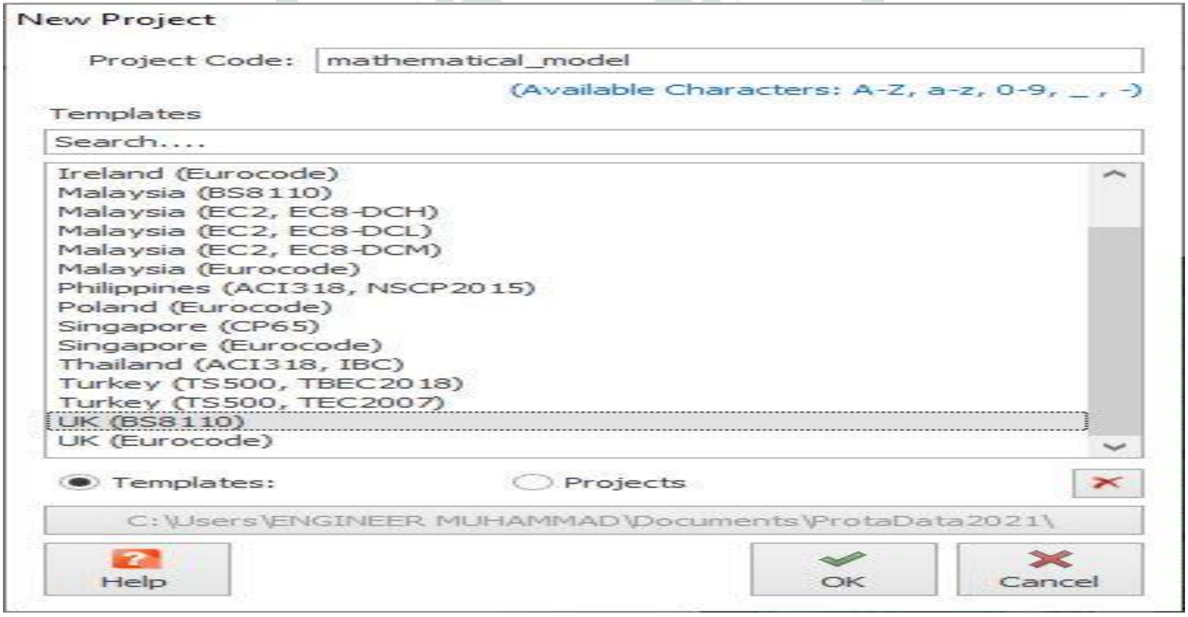
Figure 2: Summary Procedure.

### 5.2.1 Analysis and Design of summary Procedure Using PROTA and Minitab Software.

### STEP1: MODELLING OF 15 STOREY RC FRAME STRUCTURE

**a)** Start-up ProtaStructure and Opening Project Dialog.

**b)** Importing template for BS8110 based design in ProtaStructures. (Fig, 3)


New Project

Project Code: mathematical_model

(Available Characters: A-Z, a-z, 0-9, _ , -)

Templates

Search....

Ireland (Eurocode)
Malaysia (BS8110)
Malaysia (EC2, EC8-DCH)
Malaysia (EC2, EC8-DCL)
Malaysia (EC2, EC8-DCM)
Malaysia (Eurocode)
Philippines (ACI318, NSCP2015)
Poland (Eurocode)
Singapore (CP65)
Singapore (Eurocode)
Thailand (ACI318, IBC)
Turkey (TS500, TBEC2018)
Turkey (TS500, TEC2007)
UK (BS8110)
UK (Eurocode)

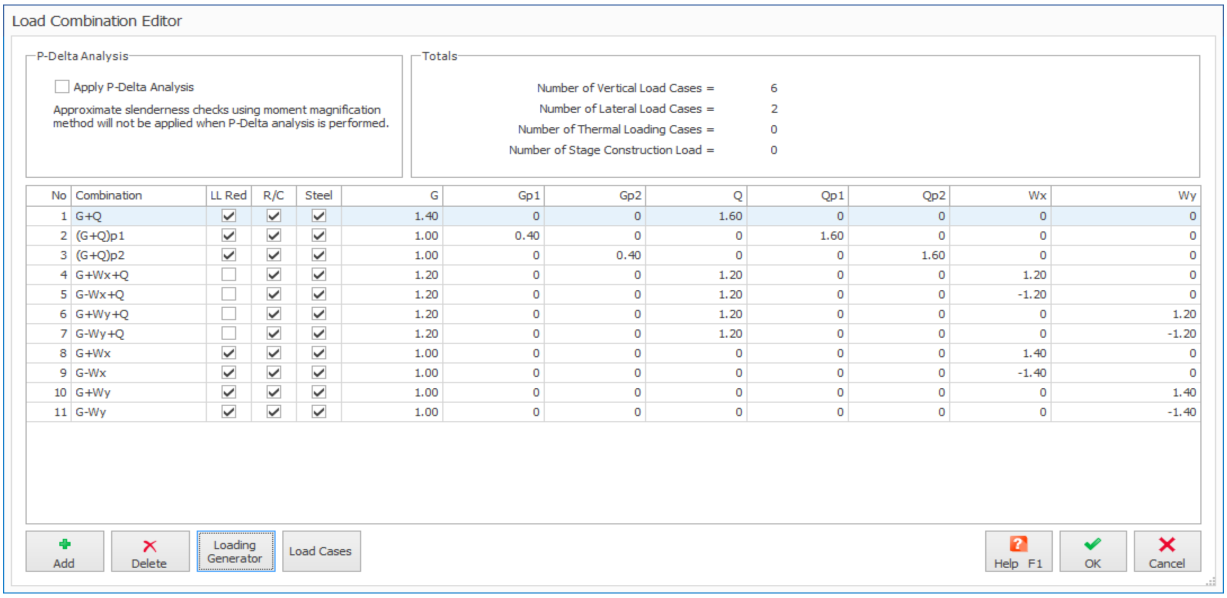
● Templates: ○ Projects

C:\Users\ENGINEER MUHAMMAD\Documents\ProtaData2021\

Figure 3: Importing template for BS8110 based design

### STEP2: ADDITION OF LATERAL LOAD TO EACH STOREY (i.e. 3-15 storeys)

- Parameters to review and modify the design codes and notional horizontal load, foundation soil allowed stress, lateral loading and lateral drift were default.
- Load Combination are to generate sets (vertical and horizontal load combination) (Fig. 4).



☐ Apply P-Delta Analysis

Approximate slenderness checks using moment magnification method will not be applied when P-Delta analysis is performed.

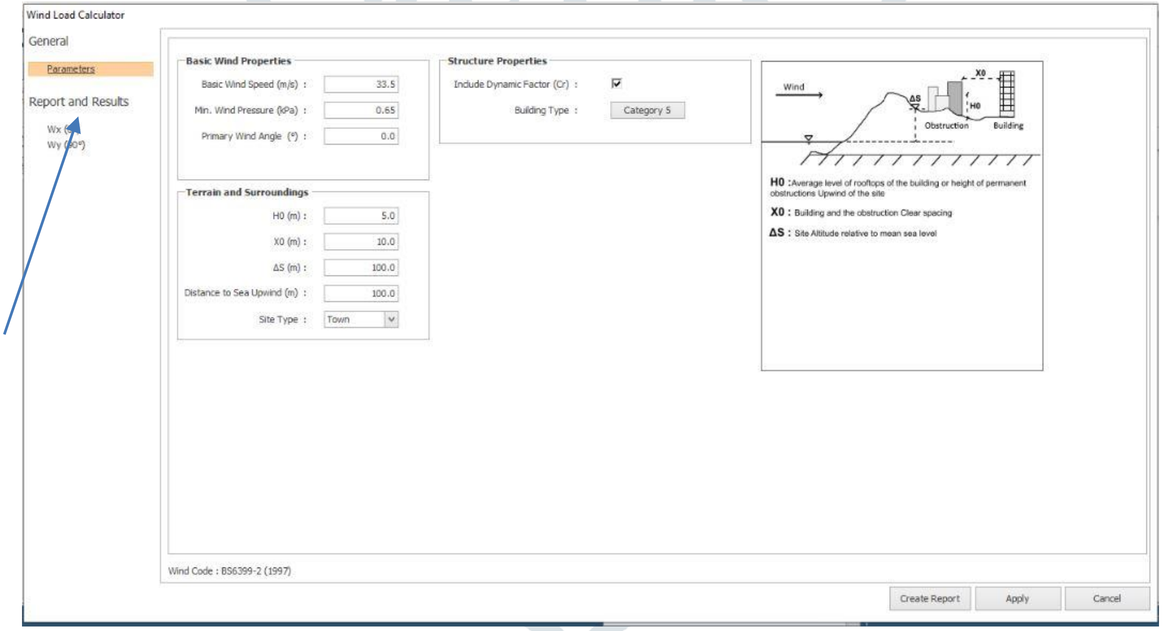
Number of Vertical Load Cases = 6
Number of Lateral Load Cases = 2
Number of Thermal Loading Cases = 0
Number of Stage Construction Load = 0

| No | Combination | LL Red | R/C | Steel | G | Gp1 | Gp2 | Q | Qp1 | Qp2 | Wx | Wy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | G+Q | ☑ | ☑ | ☑ | 1.40 | 0 | 0 | 1.60 | 0 | 0 | 0 | 0 |
| 2 | (G+Q)p1 | ☑ | ☑ | ☑ | 1.00 | 0.40 | 0 | 0 | 1.60 | 0 | 0 | 0 |
| 3 | (G+Q)p2 | ☑ | ☑ | ☑ | 1.00 | 0 | 0.40 | 0 | 0 | 1.60 | 0 | 0 |
| 4 | G+Wx+Q | ☐ | ☑ | ☑ | 1.20 | 0 | 0 | 1.20 | 0 | 0 | 1.20 | 0 |
| 5 | G-Wx+Q | ☐ | ☑ | ☑ | 1.20 | 0 | 0 | 1.20 | 0 | 0 | -1.20 | 0 |
| 6 | G+Wy+Q | ☐ | ☑ | ☑ | 1.20 | 0 | 0 | 1.20 | 0 | 0 | 0 | 1.20 |
| 7 | G-Wy+Q | ☐ | ☑ | ☑ | 1.20 | 0 | 0 | 1.20 | 0 | 0 | 0 | -1.20 |
| 8 | G+Wx | ☑ | ☑ | ☑ | 1.00 | 0 | 0 | 0 | 0 | 0 | 1.40 | 0 |
| 9 | G-Wx | ☑ | ☑ | ☑ | 1.00 | 0 | 0 | 0 | 0 | 0 | -1.40 | 0 |
| 10 | G+Wy | ☑ | ☑ | ☑ | 1.00 | 0 | 0 | 0 | 0 | 0 | 0 | 1.40 |
| 11 | G-Wy | ☑ | ☑ | ☑ | 1.00 | 0 | 0 | 0 | 0 | 0 | 0 | -1.40 |

Figure 4: Load combination editor.

- Storey Loads and Parameters to review and add inputs to any later loads such as wind load.
- Edit Materials to review and change the concrete grades to C20/25N/mm^2 and reinforcement material of 460N/mm^2.

**c)** Defining wind load calculator, basic wind properties; wind speed (**33.5m/s**), wind angle **($0^0$)** and minimum wind load pressure ***(1kN/m, 2kN/m, 3kN/m, 4kN/m, and 5kN/m.)***, and Terrain and surrounding, (terrain category II and default) and structural properties.as shown below (Fig.5);



Basic Wind Speed (m/s) : 33.5
Min. Wind Pressure (kPa) : 0.65
Primary Wind Angle (°) : 0.0

Include Dynamic Factor (Cr) : ☑
Building Type : Category 5

H0 (m) : 5.0
X0 (m) : 10.0
ΔS (m) : 100.0
Distance to Sea Upwind (m) : 100.0
Site Type : Town

**H0** : Average level of rooftops of the building or height of permanent obstructions Upwind of the site
**X0** : Building and the obstruction Clear spacing
**ΔS** : Site Altitude relative to mean sea level

Wind Code : BS6399-2 (1997)

Figure 5: Wind load calculator

- Assigning of wind loads was achieved after Wind loads are defined and assigned as per BS 6399:1997 PART 2: Loading for building, and change of constituent variation of wind load that was produced in the above step.

**STEP3: DESIGN THE MODEL (BUILDING ANALYSIS AND DESIGN)**

- Analysis after the completion of all the above steps was performed and checked for modelling errors.

**d)** Design after the completion of analysis, concrete design on the structure was performed as per BS8110-1:1997. PROTA performs the design for every structural element and was deemed OK (Fig. 8).

**STEP4: OBTAINING OF FORCE DISPLACEMENT RESULT (DX only)**

**e)** Obtaining from the Building Analysis menu at the Reports: Storey displacement report.

**STEP5: REGRESSION ANALYSIS ON THE RESULT (Minitab)**

**f)** Start-up Minitab Software and select **stat>>Regression>>Fits Regression Model.**

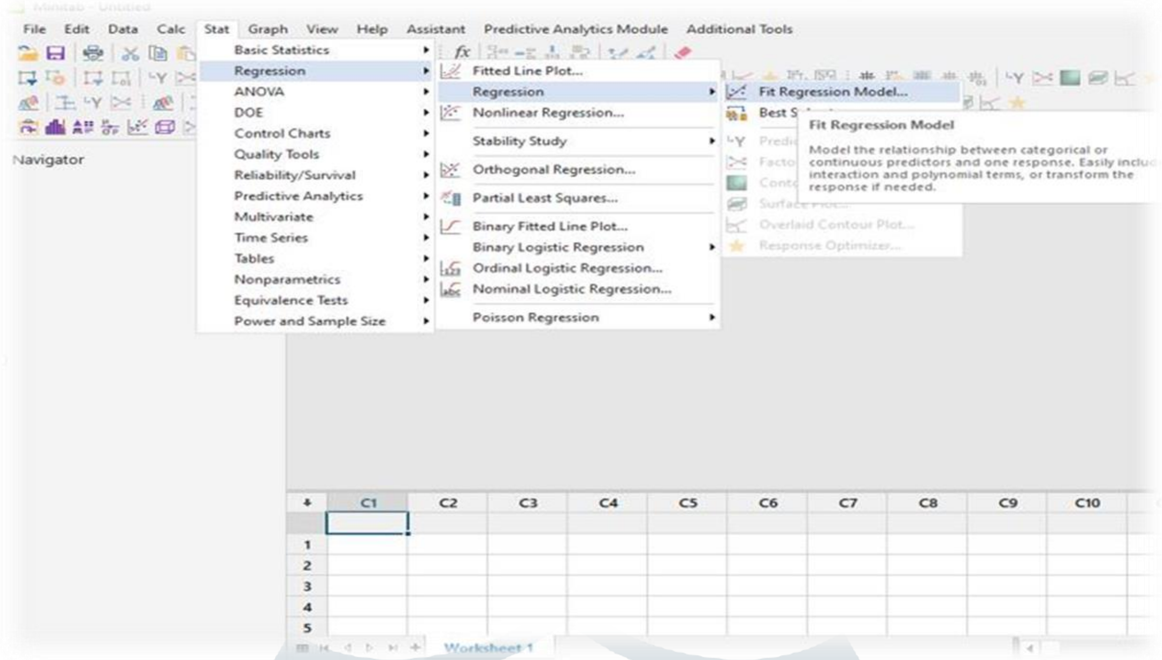


Figure 6: Regression Analysis processes.

**g)** Specify the response and the predictor(s) (Fig. 7).

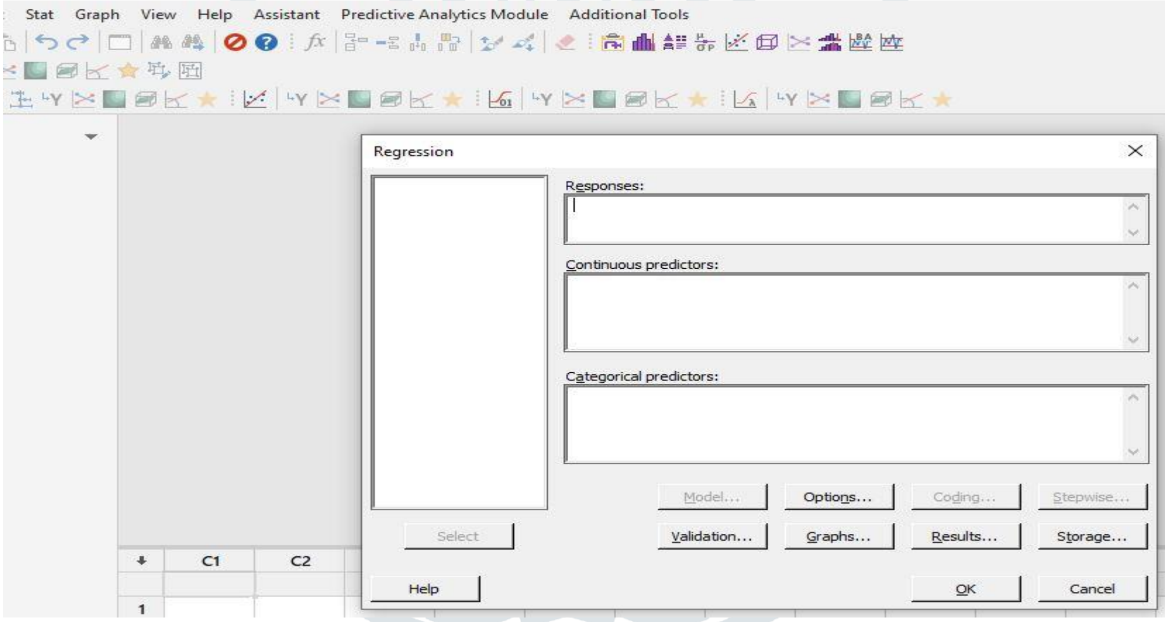


Figure 7: Response and the predictor(s) definition.

**h)** (For standard residual plots) under Graphs…, select the desired residual plots.

**i)** Minitab automatically recognizes replicates of data and produces lack of Fit test with pure error by default. And Select **OK.**

**STEP6: OBTAIN THE EQUATION (Model)**

**j)** The Regression equation was obtained from the above step result.

## 6. RESULTS AND DISCUSSION

### 6.1 Designed frame High Rise RC Building Structure

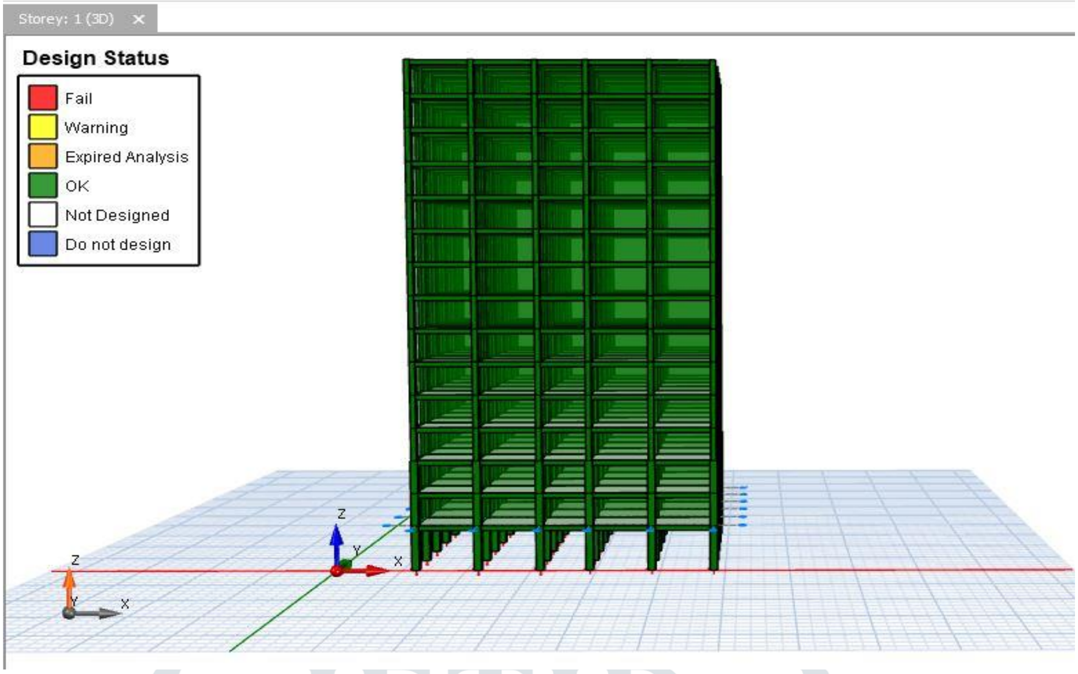


Figure 8: Design Status for frame high rise RC structure.

Figure 8 shows a frame design for high rise RC building structure, which was developed with ProtaStructure and indicated that the design status was sufficiently OK.

### 6.2 Results of Descriptive Statics of Study Variables

**Table 6.2: Summary of displacements report extracted from ProtaStructure post-analysis results.**

| Load Case | Floors/storeys | Displacement (mm) for 1 (kN/m^2) | Displacement (mm) for 2 (kN/m^2) | Displacement (mm) for 3 (kN/m^2) | Displacement (mm) for 4 (kN/m^2) | Displacement (mm) for 5 (kN/m^2) |
|---|---|---|---|---|---|---|
| Wx | 3 | 5.2589 | 7.5917 | 11.3880 | 15.1830 | 18.9790 |
| Wx | 4 | 7.6197 | 10.8930 | 16.3400 | 21.7860 | 27.2330 |
| Wx | 5 | 9.9009 | 14.0180 | 21.0270 | 28.0370 | 35.0460 |
| Wx | 6 | 12.0440 | 16.9070 | 25.3600 | 33.8140 | 42.2670 |
| Wx | 7 | 14.0840 | 19.6240 | 29.4360 | 39.3480 | 49.0600 |
| Wx | 8 | 16.0040 | 22.1600 | 33.2400 | 44.3190 | 55.3990 |
| Wx | 9 | 17.7140 | 24.4020 | 36.6020 | 48.8030 | 61.0040 |
| Wx | 10 | 19.1910 | 26.3270 | 39.4910 | 52.6540 | 65.8180 |
| Wx | 11 | 20.4270 | 27.9310 | 41.8970 | 55.8620 | 69.8280 |
| Wx | 12 | 21.4160 | 29.2120 | 43.8180 | 58.4240 | 73.0290 |
| Wx | 13 | 22.1590 | 30.1710 | 45.2560 | 60.3410 | 75.4260 |
| Wx | 14 | 22.6610 | 30.8180 | 46.2270 | 61.6350 | 77.0440 |
| Wx | 15 | 22.9610 | 31.2070 | 46.8100 | 62.4140 | 78.0170 |

The above table shows all the displacements of the load cases (Wx) i.e. wind loading and direction at $(0^{o})$ that were extracted in the ProtaStructures post analysis and also to be used as input data for ANOVA in Minitab. From the displacement results shown above, it was evident that the higher the storey/force the more the displacement.

**Table 6.3: Model summary**

| S | R-sq | R-sq.(adj) | PRESS | R-sq.(pred) | AICc | BIC |
|---|---|---|---|---|---|---|
| 0.537652 | 86.21% | 85.77% | 19.9739 | 84.64% | 109.39 | 117.42 |

Table 6.3 above shows the model which has an R-squared of **86.21%,** which indicates that the independent variables account for a significant portion of the variation in the dependent variable.

**Table 6.4: Analysis of variance (ANOVA)**

| Source | DF | Seq. SS | Contribution | Adj. SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| Regression | 2 | 112.078 | 86.21% | 112.08 | 56.039 | 193.86 | 0.000 |
| FL | 1 | 0.000 | 0.00% | 40.14 | 40.136 | 138.85 | 0.000 |
| DX | 1 | 112.078 | 86.21% | 112.08 | 112.078 | 387.72 | 0.000 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Error | 62 | 17.922 | 13.79% | 17.92 | 0.289 | | |
| Total | 64 | 130.000 | 100.00% | | | | |

Table 6.4 shows Analysis of variance (ANOVA) table showing that both FL and DX have a significant contribution to the model.

## 7. FINDINGS

1. A frame design for high rise building structure, analysis, and design was obtained for selected key elements, however only some few key elements where displayed due to the large volume of the results report. As the model was successfully designed with the loading conditions and combinations.
2. By defining the displacement, wind load calculator, are generated towards basic wind properties; wind speed (33.5m/s), wind angle (0.0) degree and minimum wind load pressure which were changing i.e. (1kN/m^2, 2kN/m^2, 3kN/m^2, 4kN/m^2, and 5kN/m^2.), respectively that produces the loads constituent to each storeys starting from (3-15 storeys) and results was successfully obtained from ProtaStructures post analysis reports also to be used in the further objectives. From the results obtained, it was clear that the higher the storey/force the more the displacement.
3. The results in the analysis of building, (i.e. the displacements) were obtained and serves as input data for the regression analysis.
4. The regression equation F = 2.430 - 0.2621 FL + 0.08460 DX was generate from the regression analysis developed from Minitab software i.e. the dependent variable "F"(load/force) and the independent variables "FL" (floor) and "DX"(displacement in X-Direction).
5. The coefficients of the equations which indicate that as FL increases by one unit, F decreases by 0.2621 units, while as DX increases by one unit, F increases by 0.08460 units.
6. The model which has an R-squared of 86.21%, which indicates that the independent variables account for a significant portion of the variation in the dependent variable.
7. The ANOVA table shows that both FL and DX have a significant contribution to the model. There are four unusual observations highlighted in the Fits and Diagnostics section, with large residuals and high Cook's D values.
8. These observations may be outliers that are influencing the model and should be investigated further. The VIF values suggest low multi collinearity between the independent variables

## 8. RECOMMENDATION

1. The mathematical modelling of force displacement in high rise frame structure is a complex process that requires a thorough understanding of the structural behavior of the frame, as such model developed can be useful for estimation any parameter in the model.
2. The results of the modelling can be used to determine the structural performance of the frame and to identify potential areas of improvement.
3. It recommended to develop a comprehensive understanding of the structural behavior of the frame before attempting to model it and utilize advanced mathematical modelling techniques such as finite element analysis.
4. Additionally, the accuracy of the data used to create the model was quite difficult to extract, however the R-squared was obtained as 86.21% and P-value is 0, as such the model is recommended fit and significant.

## 9. CONCLUSIONS

The structural elements of a frame design for high rise building structure, analysis was designed using ProtaStructures and their results were obtained, it was observed that the designed based on limit states methods as per BS8110-1:1997 and BS6399, which saw the model successfully designed and the regression equation generated as F = 2.430 - 0.2621 FL + 0.08460 DX. This indicates that the model with an R-squared of 86.21%, has the independent variables account for a significant portion of the variation in the dependent variables and P-value = 0, indicating a good fit of the developed model.

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