Analysis of tall building for across wind response

Arvind Y. Vyavahare¹, Godbole. P.N², Trupti Nikose³

1- Assistant Professor, Visvesvaraya National Institute of Technology Nagpur, INDIA
2- Emeritus Professor R.K.N.E.C. Nagpur, INDIA
3- Teaching Assistant, G.H.R.C.E. Nagpur, INDIA
ayv@apm.vnit.ac.in
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ABSTRACT

Tall buildings are slender flexible structures and need to be investigated to ascertain the importance of wind induced oscillations or excitation along and across the direction of wind. The Indian code of practice for wind load on buildings and structures (IS-875 Part-3 1987) gives a procedure to determine along wind response of tall structures, while the across wind response and interference effect are not included in the code at present. A document ‘Review of Indian Wind Code IS 875 (Part 3) 1987’ has been prepared by IIT Kanpur under GSDMA project gives recommendations to obtain across wind response of tall buildings as per procedure given in Australian/New Zealand standard ‘Structural Design Actions – Part 2 Wind Action (AS/NZS 1170-2 : 2002)’. In the Australian code to obtain the cross wind response it is necessary to compute the coefficient (Cfs) for which figures and expressions are given for selected (h:b:d) ratios. In this paper use of Artificial Neural Network (ANN) has been made to generalize the above procedure from the limited available data, so that across wind response can be obtained for a building with given (h:b:d) ratio.

Keywords: Wind analysis, ANN, Across-wind response, Tall structures, MATLAB.

1. Introduction

Tall Buildings are a common feature these days in both developed and developing economies and with the increase in population and lack of open spaces instead of single storied constructions, multi-storied buildings are increasingly becoming popular and hence special consideration need to be given for the analysis of these structures by considering the dynamic nature of wind.

As the demand for taller, lighter and more slender structures continues to increase, so does the importance of designing for wind induced building motion. Tall structures that meet the code for lateral drift requirements can still sway in strong winds. The recent disasters in United States due to the hurricanes also prove that existing buildings are not fully wind resistant. Therefore it becomes necessary to review the computing techniques that are currently in use for the determination of along and across wind load. (Ahsan, 1988), (Mendis et. al., 2007) have discussed importance of across wind response of tall and slender structures. (Prem Krishna et. al., 2004a, 2004b), have prepared draft & commentary for proposed revision of IS: 875 (Part-3) and included method for calculating across wind forces on tall structures.

It is believed that the wind load estimation will be made by taking into account the random variation of wind speed with time but available theoretical methods have not matured sufficiently at present for use in the Indian Standard Code. For this reason, static wind
method of load estimation has been suggested, which implies a steady wind speed, proved to be satisfactory for normal, short and heavy structures.

The catastrophic damage to life and property due to wind storms is experienced in many parts of the world including India, which has encouraged many investigations on the determination of wind loads on different structures. Usually the evaluation of wind loads in Buildings is carried out using codes and standards, whose specifications are generally based on wind tunnel tests performed on selected building structures with common shapes. For example in India, IS: 875- (Part-3)-1987 gives specifications for rectangular square, cylindrical shapes and some typical Industrial Structures. Wind pressure determination in buildings having shapes different from those specified in codes and standards requires wind tunnel studies.

2 ANN for across wind response

Application of ANN in wind engineering started rather late (James, 1994), (Flood and Kartam, 1994), (Rafiq and Bugmann, 2001), (Rao and Datta, 2006) have demonstrated use of ANN in complex civil engineering structural analysis and also in seismic analysis of structure. Application suggested by (Khanduri et.al., 1995), in which the use of Neural Network approach for assessment of wind induced interference effects on design load for building has been discussed. (Girma and Godbole, 1999) had developed two ANN program, first based on Back Propagation Learning Network (BPLN) and the other based on Cascade Co-relation Learning Network (CCLN) and demonstrated its use to determine pressure distribution for large multistoreyed office building for which limited wind tunnel test data was available. (Kwatra et. al., 2002) in his detailed studies carried out experimental studies on wind induced pressure on gable roof. He further utilized this limited test data and developed an ANN model for predicting wind induced pressures in various zones of gable buildings in a stand-alone situation as well as for interference with another similar building.

In the present study use of ANN has been made to generalize determination of cross wind response for a tall building with given (h:b:d) ratio from the limited data available for h:b:d ratios of 3:1:1, 6:1:1, 6:2:1 and 6:1:2. A computer program generated data sets which were used for training and testing the neural network, using the Back Propagation Neural Network tool available in the MATLAB package.

2.1 Cross-wind response of Tall enclosed buildings of rectangular cross-section

Analysis of tall structure for cross-wind is as follows,

2.1.1 Equivalent static wind force

The equivalent cross-wind static wind force per unit height \( W_e \) as a function of \( z \) in Newton per meter height shall be as follows:

\[
W_e(z) = 0.6\sqrt{\frac{d}{h}}C_{dyn}
\]

\[C_{dyn} = 1.5gR \left( \frac{b}{d} \right) \frac{K_m}{(1 + g y l_h)^2} \left( \frac{z}{h} \right)^k \sqrt{\frac{\pi C_{fs}}{\beta}} \]

Where,

\( d \) = Lateral dimension of the structure parallel to the wind stream, and
\( K_m \) = mode shape correction factor for cross-wind acceleration
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\[ k = 0.76 + 0.24 \, k \]

\[ k = \text{mode shape power exponent for the fundamental mode of vibration.} \]

\[ = 1.5 \text{ for a uniform cantilever} \]

\[ = 0.5 \text{ for a slender framed structure (moment resistant)} \]

\[ = 1.0 \text{ for building with central core and moment resisting façade.} \]

\[ = 2.3 \text{ for a tower decreasing in stiffness with height, or with a large mass at the top.} \]

\[ C_f = \text{cross-wind force spectrum coefficient generalized for a linear mode} \]

\[ g_r = \text{peak factor for resonant response (1 hour period) given by:} \]

\[ g_r = \sqrt{2 \log_e (3600 f_o)} \]

\[ g_v = \text{peak factor for the upwind velocity fluctuations, which shall be taken as 3.5.} \]

\[ l_h = \text{turbulence intensity obtained from by setting } z \text{ equal to } h. \]

\[ \beta = \text{ratio of structural damping to critical damping of a structure between heights } s \text{ and } h. \]

\[ \text{taken as 0.02 (Reinforced or pre-stressed concrete structure)} \]

2.1.2 Cross-wind base overturning moment

The cross-wind base overturning moment \((M_0)\) in Newton-meters is given by:

\[ M_0 = 0.5 g_r b \left[ \frac{0.6(V_z)^2}{(1 + g_v I_h)^2} \right] h^2 \left( \frac{3}{k + 2} \right) K_m \sqrt{\frac{\pi C_f}{\beta}} \]

(3)

Where the value \(3K_m / (k + 2)\) is the mode shape correction factor for cross-wind base overturning moment.

2.1.3 Cross-wind force spectrum coefficient \((C_f)\)

The reduced velocity \((V_n)\) shall be calculated as follows

\[ V_n = \frac{V_z}{f_o b (1 + g_v I_h)} \]

(4)

Values of the cross-wind force spectrum coefficient \((C_f)\) generalized for a linear mode shape shall be calculated from the reduced velocity \((V_n)\).

For preparation of computer program, value of \(I_z\) (turbulence intensity) is calculated using the following formulas. In wind code, for calculation of \(I_z\) values table is given.

\[ I_z = \text{Turbulence Intensity at height } z \]

\[ Zo = \text{Aerodynamics Roughness Height} \]

Following are aerodynamic roughness heights for terrain categories 1 to 4 (TC-1 to TC-4),

\[ Zo_1 = 0.002m, Zo_2 = 0.02m, Zo_3 = 0.2 m \text{ and } Zo_4 = 2.0m \]
Turbulence intensities for corresponding terrain category are given by following equations,

\[
I_{z1} = 0.3507 - 0.0535 \log_{10} \left( \frac{Z}{Z_{01}} \right) \quad I_{z4} = 0.466 - 0.1358 \log_{10} \left( \frac{Z}{Z_{04}} \right)
\]

\[
I_{z2} = \frac{I_{z1} + 1}{I_{z4} - I_{z1}} \quad I_{z3} = \frac{I_{z1} + 3}{7(I_{z4} - I_{z1})}
\]

(5)

Similarly as discussed above, for determination of Cfs plots are given in draft code of IS 875 (Part: 3). However these are not convenient to use in programming. For the calculation of Cfs in data generation program following formulae are used. (AS/NZS :1170 Part–2 )

\[
C_{fs} = \text{cross-wind force spectrum coefficient}
\]

\[
\log_{10} C_{fs} = A_1 V_n^4 + A_2 V_n^3 + A_3 V_n^2 + A_4 V_n + A_5
\]

(6)

\[
\log_{10} C_{fs} = \frac{A_1 V_n^4 + A_3 V_n^2 + A_5}{1 + A_2 V_n^4 + A_4 V_n^2}
\]

(7)

The constants \(A_1, A_2, \ldots, A_5\) are as given in Table-1 and plot of \(C_{fs}\) in Figure 1.

| Aspect ratio h:b:d | \(I_h\) at 2h/3 | \(A_1\) | \(A_2\) | \(A_3\) | \(A_4\) | \(A_5\) | Equation |
|-------------------|----------------|--------|--------|--------|--------|--------|----------|
| 3:1:1             | 0.12           | 0.000353 | -0.0134 | 0.15   | -0.345 | -3.109 | (6)      |
|                   | 0.20           | 0.00008 | -0.0028 | 0.0199 | 0.13   | -2.985 |          |
| 6:1:1             | 0.12           | 0.000406 | -0.0165 | 0.201  | -0.603 | -2.76  |          |
|                   | 0.20           | 0.000334 | -0.0125 | 0.141  | -0.384 | -2.36  |          |
| 6:1:2             | 0.12           | 0 | 0.000457 | -0.0226 | 0.396 | -4.093 |          |
|                   | 0.20           | 0 | 0.00038 | -0.0197 | 0.363 | -3.82  |          |
| 6:2:1             | 0.12           | -0.00039 | 0.000123 | 0.0683 | -0.02 | -3.2   | (7)      |
|                   | 0.20           | -0.00037 | 0.000124 | 0.0637 | -0.02 | -3.0   |          |

3. Input and output data

The present Indian Standard code of practice IS 875 (Part-3) -1987 is almost silent about the wind response of tall buildings for across wind direction. But Review of IS 875 (Part-3) – 1987 Document No. IITK – GSDMA – Wind-01 V 2.0, IITK – GSDMA has given the provisions to determine the response for across wind direction. Document has given the charts for the cross wind response spectrum for the specific dimension ratios of the building i.e. for 6:1:1, 3:1:1, 6:1:2 and 6:2:1 respectively.
Height of building (H) varies from 100 m to 260 m. The breadth and depth of building is depend upon the h:b:d ratio 3:1:1, 6:1:1, 6:2:1 and 6:1:2. Responses have been calculated under four different terrain categories i.e. TC-1, TC-2, TC-3 and TC-4. These responses are generated by variation of basic wind speed V_b i.e 33 m/s, 39 m/s, 44 m/s, 47 m/s, 50 m/s & 55 m/s respectively. Total 4800 such data sets have been generated by using the available package which are then used in training and testing of the Neural Network. The objective of this is to create a neural network which can determine the Shear Force and Bending Moment in tall buildings for across wind direction.

To train the neural network, the data sets are divided into two parts viz. training data set and testing data set. This is done to give an indication of how well the neural network has learnt to make predictions for the data which is not been used in the past. Number of data points used in training of Neural Network are varied randomly from 1487 to 4500, out of that testing data point set software itself divides the 60% data for training, and 15% each for testing and validation purpose. However the percentage of data points for training, testing and validation can suitably adjusted. Separate data point sets can also be provided for validation purpose.
After training the neural network, selected data patterns are used to test the performance of the network for the new data. Some of the results obtained are given in Figure 2 and Figure 3.

Figure 3: Normalized response of tall buildings (A) Shear force (B) Bending Moment

4. Use of developed neural network to predict across wind response

There are some limitations for calculating across wind response of tall buildings. As per code, for $h:b:d$ ratio $3:1:1, 6:1:1, 6:2:1$ & $6:1:2$ only, wind response in across direction can be determined. So to expand the solution for across wind direction ANN can be used.

| Input | Normalized Shear force and Bending Moment (Multiplier: for SF $\rightarrow 31670.809$ kN) |
|-------|-----------------------------------------------------------------------------------|
|       | 1487 Data Pts Set | 2500 Data Pts Set | 3500 Data Pts Set | 4500 Data Pts Set |
| $h$   | $b$ | $d$ | $V$ | $TC$ | 0.1060 | 0.1046 | 0.1058 | 0.1057 |
| 115   | 40  | 20  | 55  | 4.0 | 0.1063 | 0.1067 | 0.1063 | 0.1066 |
| 150   | 30  | 20  | 39  | 1.0 | 0.1051 | 0.1061 | 0.1057 | 0.1067 |
| 85    | 26.5| 26.5| 47  | 2.0 | 0.2388 | 0.2368 | 0.2388 | 0.2367 |
| 165   | 55  | 55  | 47  | 3.0 | 0.1240 | 0.1240 | 0.1240 | 0.1249 |
| 180   | 55.5| 40.5| 33  | 4.0 | 0.0353 | 0.0345 | 0.0353 | 0.0348 |
| 105   | 36  | 36  | 33  | 4.0 | 0.2153 | 0.2153 | 0.2153 | 0.2152 |
| 205   | 30  | 70  | 44  | 1.0 | 0.2796 | 0.2790 | 0.2796 | 0.2792 |
| 215   | 30  | 36  | 47  | 3.0 | 0.2803 | 0.2831 | 0.2801 | 0.2809 |
| 175   | 29  | 29  | 55  | 2.0 | 0.1276 | 0.1264 | 0.1264 | 0.1288 |
| 145   | 40  | 50  | 39  | 1.0 | 0.4349 | 0.4359 | 0.4365 | 0.4360 |
| 250   | 40  | 30  | 47  | 3.0 | 0.4569 | 0.4596 | 0.4609 | 0.4630 |

Some Data are taken randomly, other than, $h:b:d$ ratio covered in study. This Data are tested using Different sets of data points, with considering case Five Inputs Two Outputs using single as well as double hidden layer. Table 2 and Table 3; gives the predicted normalized values of shear force and bending moments using Neural Networks with Double Hidden Layer and with 20 Neurons in each layer.
Table 3: Predicted Normalized Bending Moment

| Input | Normalized Shear force and Bending Moment (Multiplier: for BM → 5643284.581kN-m) |
|-------|----------------------------------------------------------------------------------|
|       | 1487 Data Pts Set | 2500 Data Pts Set | 3500 Data Pts Set | 4500 Data Pts Set |
| h     | b     | d     | V     | TC       | 0.0570 | 0.0565 | 0.0570 | 0.0575 |
| 115   | 40    | 20    | 55    | 4        | 0.0726 | 0.0726 | 0.0719 | 0.0724 |
| 150   | 30    | 20    | 39    | 1        | 0.0183 | 0.0181 | 0.0183 | 0.0183 |
| 85    | 26.5  | 26.5  | 47    | 2        | 0.0719 | 0.0702 | 0.0701 | 0.0704 |
| 165   | 55    | 55    | 47    | 3        | 0.1763 | 0.1779 | 0.1761 | 0.1762 |
| 180   | 55.5  | 40.5  | 33    | 4        | 0.1098 | 0.1048 | 0.1043 | 0.1040 |
| 105   | 36    | 36    | 33    | 4        | 0.0173 | 0.0173 | 0.0173 | 0.0173 |
| 205   | 30    | 70    | 44    | 1        | 0.2049 | 0.2019 | 0.2028 | 0.2013 |
| 215   | 30    | 36    | 47    | 3        | 0.2743 | 0.2713 | 0.2728 | 0.2710 |
| 175   | 29    | 29    | 55    | 2        | 0.2277 | 0.2277 | 0.2277 | 0.2257 |
| 145   | 40    | 50    | 39    | 1        | 0.0858 | 0.0858 | 0.0853 | 0.0853 |
| 250   | 40    | 30    | 47    | 3        | 0.4678 | 0.4681 | 0.4681 | 0.4696 |

From the above study we can say that for double hidden layer with 20 neurons in each layer gives more accurate results.

5. Conclusions

The curves for values as per IS 875 (Part-3) draft and ANN predicted values of various responses for across wind direction (Shear force and Bending moment) are almost overlapping each other which indicates close agreement between ANN predicted values and values as per IS 875 (Part-3) draft code.

In the present study network has been trained for single as well as double hidden layer. Curves for ANN predicted values for double hidden layer match reasonably well as compared to the values for single hidden layer which indicates that more number of hidden layers results in the better training results.

Different training functions (i.e. trainlm, trainbr etc.) are available to train the neural network. Out of that trainlm is the fastest training function and require less number of epochs as compared to other in training functions.

In this study, 1487, 2500, 3500 & 4500 sample data point’s sets have been used to train the network. For 4500 sample data point sets results are more accurate. Increasing number data points in a set reduces error. It is observed that sample data patterns should be large and representative to achieve better training results for the neural network.

In draft code IS 875 Part-3; there are some limitations for calculating across wind response of tall buildings. Across wind response, only for h:b:d ratio 3:1:1, 6:1:1, 6:2:1 and 6:1:2 can be determined as per code. In Table 2 the results for h:b:d ratio 5.8:2:1, 7.5:1.5:1, 3:1:1, 5.7:1:1, 3:1:1, 4.4:1.4:1, 2.9:1:1, 2.9:0.4:1, 6:0.8:1, 6:1:1, 2.9:0.8:1, 8.3:1.3:1 are summarized, it shows the ANN has capability to determine across wind response of tall buildings for all other ratios also.
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