Landscape Architecture and Regional Planning
2016; 1(1): 49-54
http://www.sciencepublishinggroup.com/j/larp
doi: 10.11648/j.larp.20160101.17

Review Article

A Comparative Study for Dynamic Responses of Tall Buildings Due to Wind Load Distribution Patterns

Thida Htun

Department of Civil Engineering, Nationalities Youth Resource Development Degree College, Yangon, The Republic of the Union of Myanmar

Email address:
thidahtun08@gmail.com

To cite this article:
Thida Htun. A Comparative Study for Dynamic Responses of Tall Buildings Due to Wind Load Distribution Patterns. *Landscape Architecture and Regional Planning.* Vol. 1, No. 1, 2016, pp. 49-54. doi: 10.11648/j.larp.20160101.17

Received: November 26, 2016; **Accepted**: December 27, 2016; **Published**: January 21, 2017

Abstract: In this study, the loading pattern of skewed and orthogonal wind condition is analysed to find how much increased or reduced response. As the height of the buildings increases, its vulnerability to wind effects also increases. Codes and Standards utilize the "gust loading factor" (GLF) approach for estimating dynamic effect on high-rise structures for 0, 45 and 90 degree. At the real situation of wind load, these conditions are not covered for strong wind responses. In order to get the responses of other skewed wind direction, various type of loading patterns is assumed to apply the wind load. For the dynamic response analysis of a structure under strong winds, the spectral response method in a frequency domain or the step-by-step integration of motion equation in a time domain is used. This paper aims to make a comparison of various loading patterns of skewed and orthogonal wind in along-wind and across-wind response with respect to the gust response factor (GRF) of dynamic wind load on tall buildings. In this study, the model building is analysed for strong wind in Yangon area and costal area. Then, comparison of maximum structural responses for strong wind is studied.

Keywords: High-Rise Flexible Structures, Gust Response Factor (GRF), Loading Patterns, Skewed Wind, Orthogonal Wind

1. Introduction

Wind is a phenomenon of great complexity because of the many flow situations arising from the interaction of wind with structures. Wind is of the most significant forces of nature that must be considered in design of buildings. The characteristics of wind-induced loads on buildings continuously vary in temporal and spatial dimensions. Adequate design of buildings depends on the success in predicting the actual effects of turbulent wind forces in order to account for the most critical design scenarios which may occur during a certain design period. Along-wind force fluctuations are generated to a large extent by approaching flow turbulence, but fluctuations in across-wind force and torsion are generally dominated by vortex shedding causing asymmetric pressure distributions around building envelopes. Wind causes a three-dimensional dynamic load which varies on building surfaces in both, space and time. Meteorological data, geographical information, in addition to building geometries and surroundings affect significantly the variation of the turbulent wind loads on buildings [1]. Myanmar is vulnerable to cyclone from Bay of Bengal during pre and post monsoon seasons from April to May and from October to November. These cyclones are causes for heavy rains, floods and storms, especially in the coastal region of Rakhine State-the disaster that afflicts the region every 3-4 years.

According to current state of knowledge in wind engineering, three methods are employed for evaluating the wind loads on structures. They are static analysis, dynamic analysis and wind tunnel test. The purpose of this research is to compare the gust response factor of maximum responses for various loading pattern for skewed and orthogonal wind.

2. Methodology

The gusts can be considered as static loads if the wind load increases and vanishes in a time much longer than the period for the building. Besides that, the deflection due to wind load for a very stiff structure will not be significant, and the structure also is said 'Static'. If wind gust reaches maximum value and vanish in a time interval much shorter than the period of the structure, it becomes dynamic case. In the case of dynamic structures, there is an additional interaction with the motion of the structure. When the structure is sufficiently flexible, the response to wind loads is significant to the design of the structure. The dynamic responses to the wind load depends on wind climate, atmospheric boundary layers, turbulence properties, variations of wind speed with height, aerodynamic forces and turbulence boundary layer [2].

Wind is composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the earth's surface. These eddies give wind its gusty or turbulent character. The gustiness of strong winds in the lower levels of the atmosphere largely arises from interaction with surface features. The average wind speed over a time period of the order of ten minutes or more, tends to increase with height, while the gustiness tends to decrease with height. The wind vector at a point may be regarded as the sum of the mean wind vector (static component) and the dynamic or turbulence component.A consequence of turbulence is that dynamic loading on a structure depends on the size of the eddies.

2.1. Equivalent Static Wind Load Method

The determination of the wind loads is based on ASCE7-05, which uses average 3 second gusts at 33 ft above the ground as the standard of measurement. The Analytical Method was used to get velocity pressures at each level of the building. The velocity pressure is given by

$$q_z=0.00256K_zK_{zt}K_dV^2I \tag{1}$$

Design wind pressure or suction on a building surface is given by the equation:

$$P_z = q_z\times G_f\times C_p \tag{2}$$

where, P_z= design wind pressure or suction, in psf
q_z= velocity pressure, in psf
C_p= pressure coefficient
K_{zt}= topographic factor
I= importance factor
V= basic wind speed, mph
K_d= wind directionality factor

The gust factor, G_f required for calculating design wind pressures for the main wind-force-resisting system of the building and can be calculated as

$$G_f = 0.925\left[\frac{1+1.7I_z\sqrt{(g_QQ)^2+(g_RR)^2}}{1+1.7g_vI_z}\right] \tag{3}$$

The maximum along-wind displacement and acceleration can be determined by using the following specifications in ASCE7-05[3].

$$X_{max} = \frac{\Phi_{(z)}\rho BHC_{fx}V_z^2}{2m_i(2\pi n_1)^2}KG \tag{4}$$

$$g_x = \sqrt{2\ln(n_1T)} + \frac{0.5772}{\sqrt{2\ln(n_1T)}} \tag{5}$$

$$\sigma_{\ddot{x}} = \frac{0.85\Phi_{(z)}\rho BHC_{fx}\bar{V}_z^2}{m_i}I_zKR \tag{6}$$

$$\ddot{x} = g_{\ddot{x}}\sigma_{\ddot{x}} \tag{7}$$

Where, X_{max}= maximum along-wind displacement
$\ddot{x}$ = acceleration

In ASCE7-05, the maximum acceleration at the top of the building is greater than 20milli-g, further investigation is recommended for dynamic analyses. In addition to acceleration, many other factors such as visual cues, body position and orientation, and state of mind of occupants during windstorms influence human perception of motion, a tentative acceleration limit of 1 to 3% of gravity is recommended in ASCE7-05. The lower value is considered appropriate for apartment buildings, the higher values for office buildings [3].

Table 1. *Human Sensitivity Levels against Acceleration.*

Level	Acceleration (m/sec^2)	Effect
1	< 0.05	Human cannot perceive motion.
2	0.05 – 0.1	Sensitive people can perceive motion. Hanging objects may move slightly.
3	0.1 – 0.25	Level of motion affects desk work. Longterm exposure may produce motion sickness.
4	0.25 – 0.4	Desk work becomes difficult or almostimpossible.
5	0.4 – 0.5	Difficult to work naturally and standing people may loss balance.
6	0.5 – 0.6	Unable to walk naturally.
7	0.6 – 0.7	People cannot tolerate motion or walk.
8	> 0.85	Objects begin to fall.

Source [9]

2.2. Wind Spectra

A Spectral description of the turbulence is a convenient tool to account for the energy that is contained in sequences of gusts. Wind spectrum describes the distribution of turbulence with frequency. The spectrum (i.e. spectral density function) represents the contribution of various ranges of frequencies to the variance (σ^2, square of standard deviation for wind velocity components). Wind spectra are expressed in a non-dimensional form. There are many mathematical models of wind power spectra [2].

2.3. Aerodynamic Admittance

For ideal quasi-steady conditions, the admittance function is unity by the incident turbulence across the entire spectrum and any departure from unity would be considered a departure from the quasi-steady conditions. The aerodynamic admittance functions of several cross sections were calculated and were compared with wind tunnel test results [2]. This defines as a transfer function relating the spectrum of incident vertical gusting velocity to that of associated lift.Aerodynamic admittance, χ is use to take accounts the interaction of structure and wind flow. It is a transfer function for the area-wide distribution of wind pressure and it is also a transfer function which connects between oncoming wind velocity and induced aerodynamic force [4].

2.4. Gust Response Factor

Gust Response Factor is the ratio of a peak structure response divided by the average response due to the mean wind. GRF normally accounts for a possible resonant “dynamic effect” and a “size effect”.The GRF approach consists of specifying a force F, which, if applied statically, would cause the system to reach its expected peak response. The derivation of the gust response factor proposed by Davenport that eventually found its way into the ASCE [5].

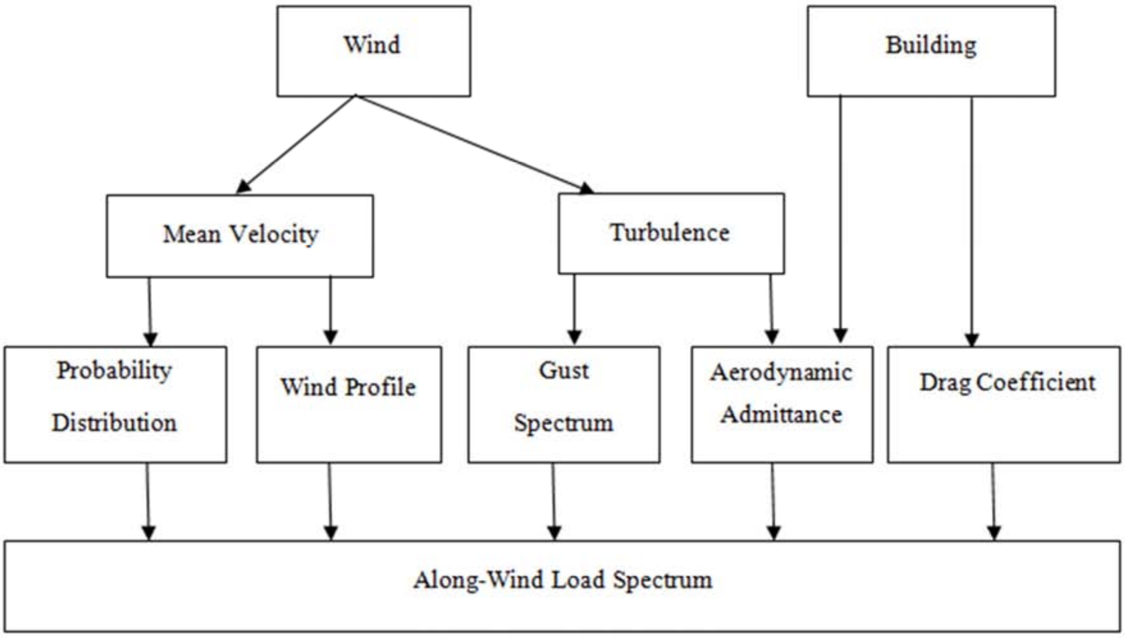

Figure 1. *Dynamic Along-wind Loads Assessment Scheme*

3. Case Studies

3.1. Hypothetical Model

The hypothetical building models are rectangular and square plan with various aspect ratios and steel building with braced frames. Beam and brace connections in the braced frames and gravity frames were modelled as pinned while beam connections in the moment frame were modelled as fully fixed. The floors are all modelled as rigid diaphragms. The building supports were modelled as fully fixed in the moment frame direction and pinned in the braced frame direction. The columns are rectangular HSS sections and all other members are typical rolled W-sections. The LRFD design philosophy was employed and members were designed to satisfy load combinations.

3.2. Case Study Programme

The equivalent static wind load is determined with Analytical Method by using Gust Factor in ASCE7-05. The model for the case study includes only the main load bearing components. Intermediate columns, and other secondary structural components and non-structural components are not included in the model.The concrete floor slabs typically have very high in-plane stiffness. Therefore they are simplified as rigid diaphragms in the model. This simplification can results a significant reduction in the size of the eigenvalue problem to be solved in the lateral (horizontal) dynamic analysis of buildings [10].

In this study, loading patterns will be considered due to each reason of conditions. Loading Pattern 1 is considered for the full wind pressure to get maximum responses and could make a building tilt. Loading Pattern 2 is used that the full wind pressure should be applied only to parts of the wall faces so that the wind-induced torsion is maximized. Loading Pattern 3&Loading Pattern 4 is studied due to the fact that a pulling and pushing horizontal pressure will reach the building simultaneously. Full pressure means the direct action of the wind and 0.75 pressure will be due to the distribution of lateral wind load on side of building. Loading Pattern 5 is considered for the consideration of torsional load case. Loading Pattern 6 & Loading Pattern 7 is studied to account for potentially more severe effects induced by diagonal wind, and also for the tendency of structures to sway in the cross-wind direction, taller structures should be designed to resist 75% of the maximum wind pressures for each of the principal directions applied simultaneously [11] [12].

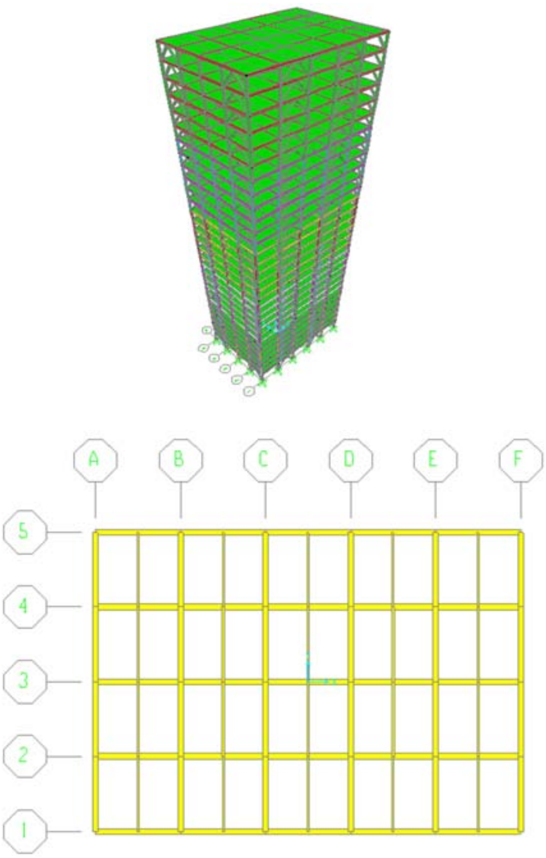

Figure 2. *3D View and Floor plan of the Model Building.*

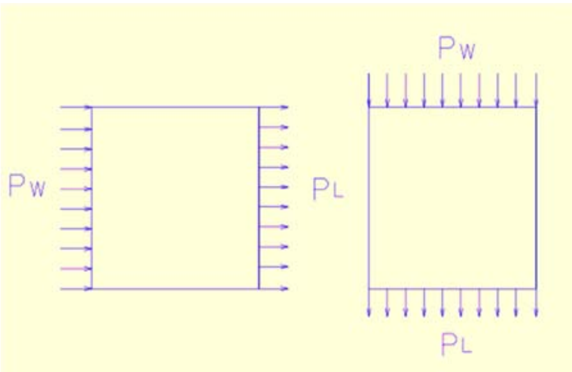

Figure 3. *Loading Pattern 1.*

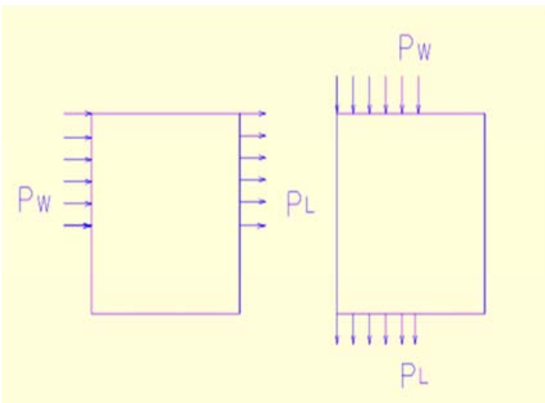

Figure 4. *Loading Pattern 2.*

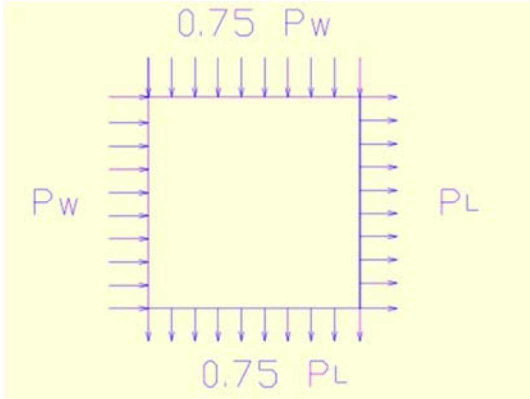

Figure 5. *Loading Pattern 3.*

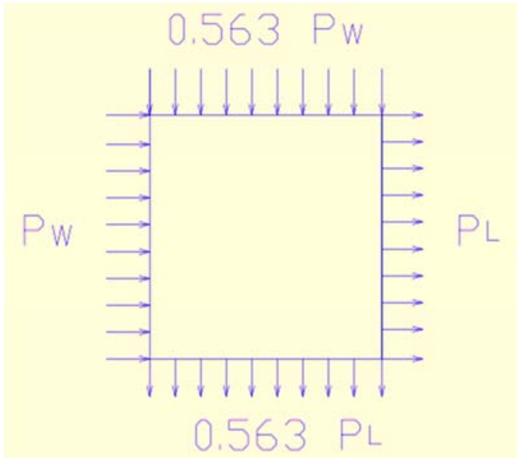

Figure 6. *Loading Pattern 4*

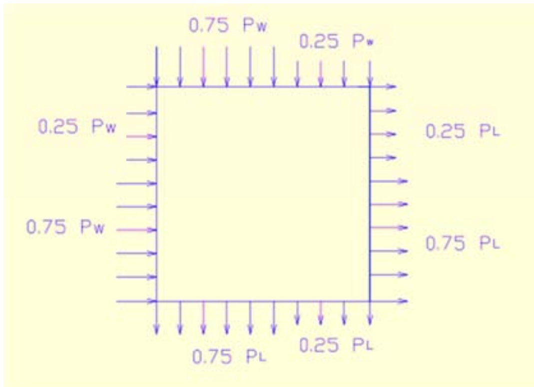

Figure 7. *Loading Pattern 5.*

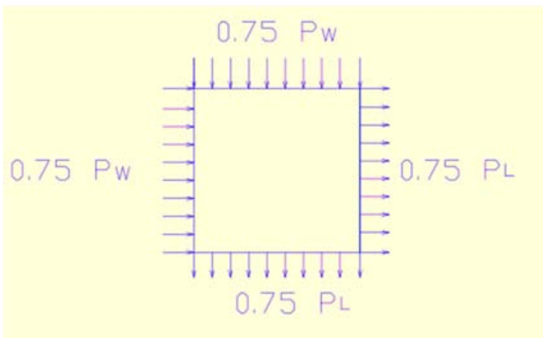

Figure 8. *Loading Pattern 6.*

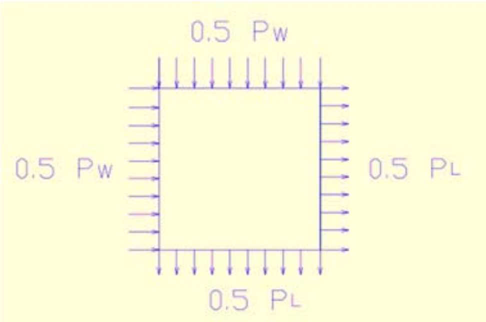

Figure 9. *Loading Pattern 7.*

Buffeting response by skewed wind and orthogonal wind is done according to the above loading patterns and flow chart.

Data for wind loads which are used in structural analysis are as follows:

(1) Building Category: - II
(2) Basic wind velocity: - 120 mph and 90 mph
(3) Exposure type: - C and B
(4) Leeward coefficient: - 0.5
(5) Windward coefficient: - 0.8
(6) Importance factor: - 1
(7) Damping ratio: - 5%

Exposure C is chosen for this study, which represent cyclonic wind areas and exposure B is chosen for Suburban. The first work is "natural frequency analysis" that gives the fundamental frequency of vibration of a building. Models are run to obtain approximate natural frequency input for the determination of gust factor in all cases of the analysis.

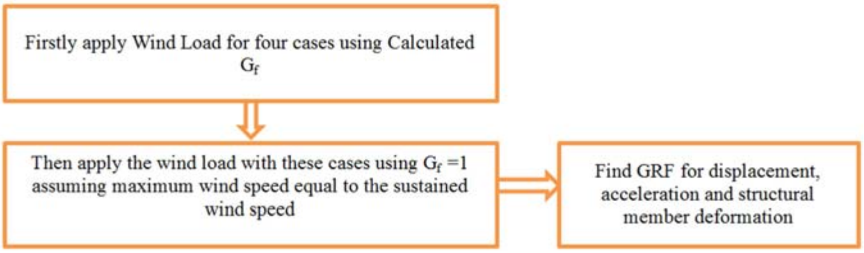

Figure 10. *Flow chart of Analysis Scheme.*

Table 2. *Building Information for Analysis.*

Building Type	Storey	Building Dimension	Slenderness Ratio	Natural frequency of Building (Hz)
Sq-1	30	75´x75´x341´	4.5	0.4
Sq-2	40	75´x75´x451´	6.0	0.3
Re-1	30	60´x100´x345´	5.6	0.3
Re-2	40	60´x100´x455´	7.5	0.2

4. Result and Discussion

In this study, the skewed wind for 30 and 60 degree is represented for scale factor in load pattern condition and then this response of case study models is compared with the difference of code defined scale factor for orthogonal wind (0 and 90 degree) and skewed wind (45 degree).The gust response factor (GRF) for each loading pattern is studied for maximum displacement, shear, moment and acceleration.

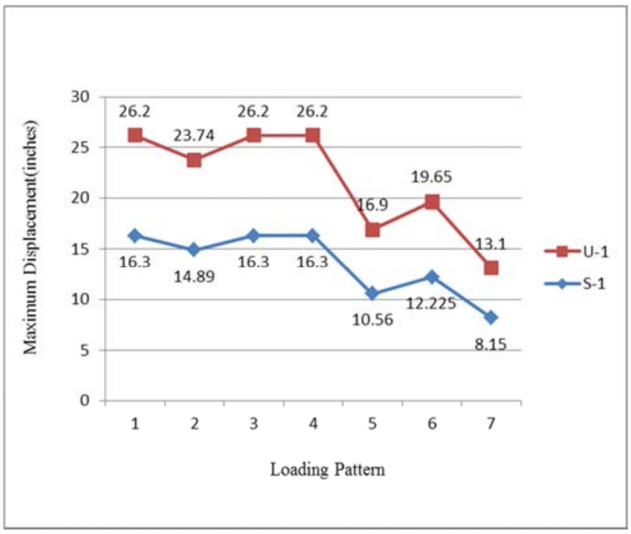

Figure 11. *Comparison of Maximum Displacement w.r.t loading patterns for 120 mph in Exposure B.*

U-1Untimate limit State
S -1Serviceability limit State

In the above figure, loading pattern 1, 3 and 4 have the same response. Loading pattern 5 and 7 show the lowest response. If the wind is to blow at a certain incidence angle from the normal to a span, the force would decrease by a factor that is equal to the square of the cosine of the incidence angle. The scale factors in various loading patterns are corresponding with a certain incidence angle from the normal to a span. For 30 degree incident angle skewed wind, scale factor 0.75 is considered and 0.5 is considered for 60 degree skewed wind.

5. Conclusion

In this study, the skewed wind for 30 and 60 degree is represented for scale factor in load pattern condition and then this response of case study models is compared with the difference of code defined scale factor for orthogonal wind (0 and 90 degree) and skewed wind (45 degree). Skew wind over 45 degree will be reduced nearly half of the total response. Thus ASCE reduces 25% of the load to cover the real condition. Orthogonal wind condition is covered for 30 and 60 degree skewed wind according to the case study. To account for potentially more severe effects induced by diagonal wind, and also for the tendency of structures to sway in the cross-wind direction, taller structures should be designed to resist 75% of the maximum wind pressures for each of the principal directions applied simultaneously. For the real sense of strong wind conditions, wind tunnel or flow simulation around the building should be done.

Acknowledgement

The author would like to acknowledge the support and encouragement of Dr. Aye Myint, Rector of the Yangon Technological University.The author would like to express her gratitude to her supervisor, Professor Dr. Nyan Myint Kyaw, Chairman of the Board of Examiners and Head of the Department of Civil Engineering of Yangon Technological University, for his valuable advice and effective help throughout the period of studies.

The author would like to express her sincere thanks to her co-supervisor Dr. Khin Aye Mon, Associate Professor of the Department of Civil Engineering of Yangon Technological University, for her encouragement, helpful suggestions and supervision.The author would like to express her heartfelt thanks to Dr. Hiromichi Shirato,Department of Civil and Earth Resources Engineering, Kyoto University, for his special lectures, helpful suggestions and for his enthusiastic instruction, invaluable help, and indispensable guidance.

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