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# Integrated Performance Based Design of Tall Buildings for Wind and Earthquakes

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AIT Solutions
Technology · Engineering · Environment · Development · Management

*The Intent of Structural Design is to*
*ensure public safety,*
*minimize damage to built environment,*
*help preserve continuity of life activities…*

# Progression of Structural Design Approaches

# Ancient masterpieces were built before the modern approaches

Master builders had freedom to dream and to realize them

Seven Wonders of the Ancient World

Great Pyramid of Giza

Hanging Gardens of Babylon

Colossus of Rhodes

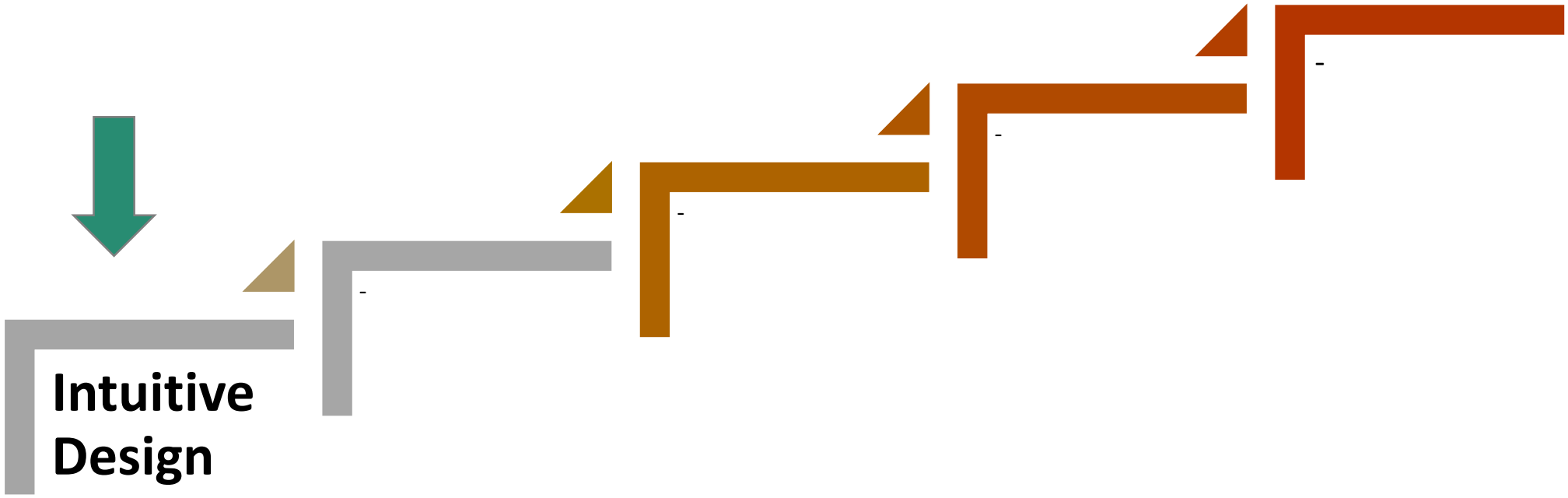
Lighthouse of Alexandria

Temple of Artemis

Statue of Zeus at Olympia

Mausoleum at Halicarnassus

# Design Approaches

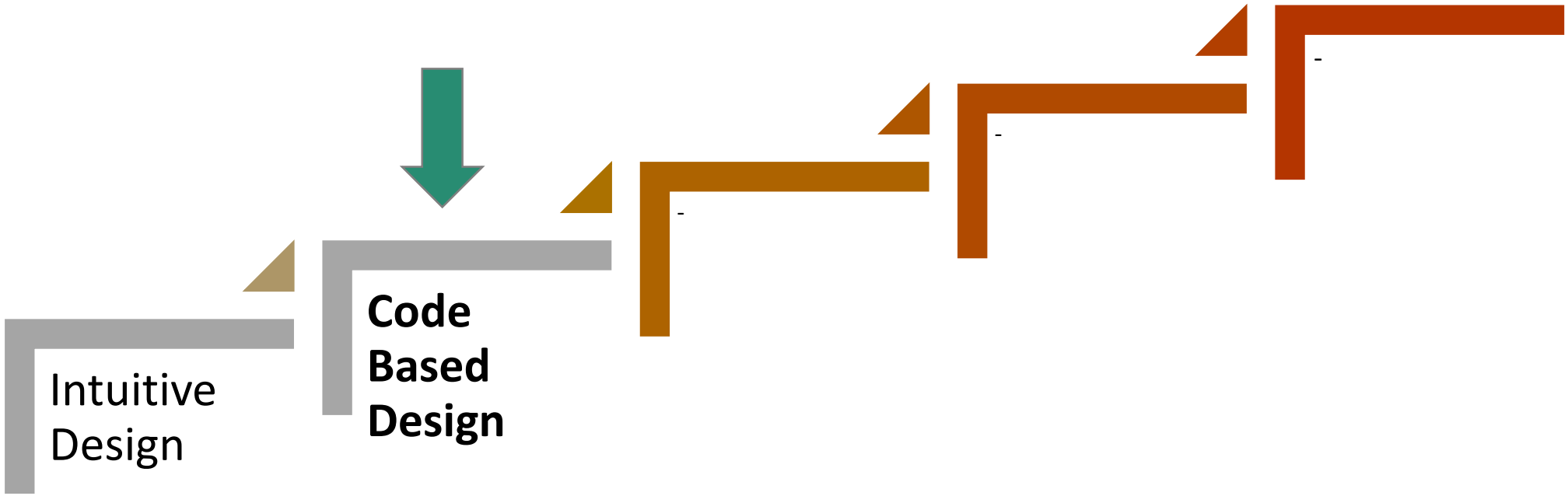


# What a Structural Engineer said !

"As the size and complexity of projects increased, … it became desirable and even necessary to … set up a series of routine procedures for analysis and design. With these standardized formulas and specifications and methods it became possible to use a greater number of men and men with less training to produce engineering works…. Standardization, as a check on fools and rascals or set up as an intellectual assembly line, has served well in the engineering world."

Hardy Cross, 1885-1959

# Design Approaches

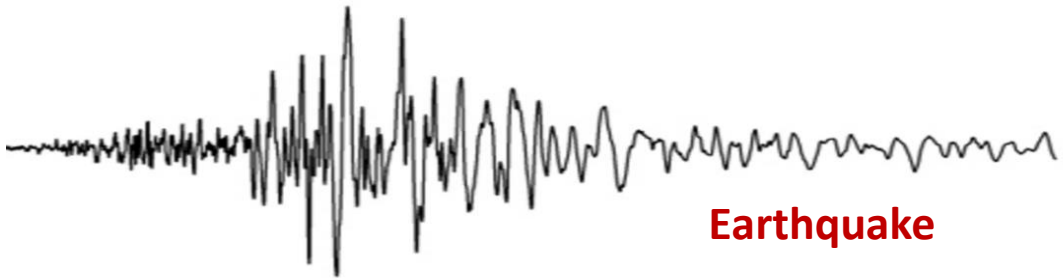


# Building Industry relies on Codes and Standards

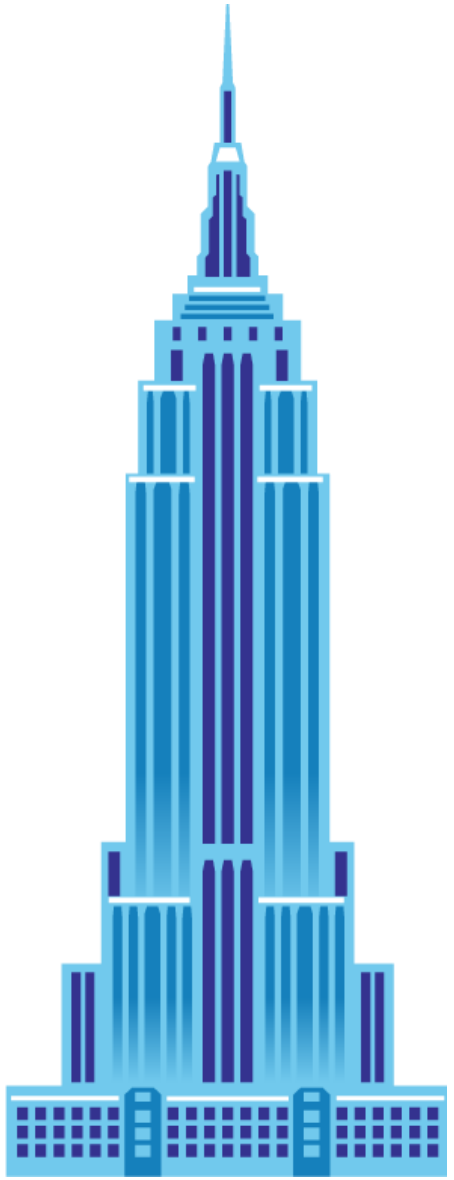
- Codes Specify requirements
- Give acceptable solutions
- Prescribe (detailed) procedures, rules, limits
- *(Mostly based on research and experience but not always rational)*

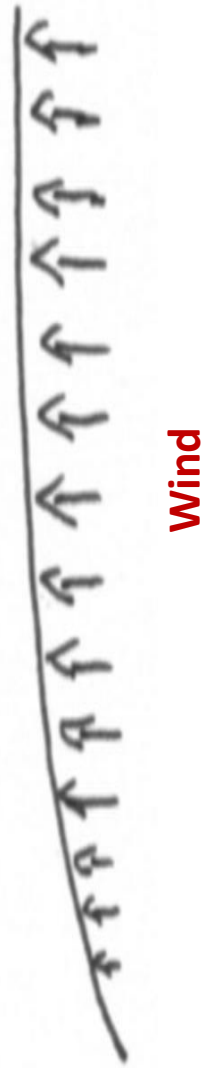
| | |
|---|---|
| Spirit of the code is to help ensure Public Safety and provide formal/legal basis for design decisions | Compliance to letter of the code is indented to meet the **spirit** |

# Main Challenges !



Earthquake





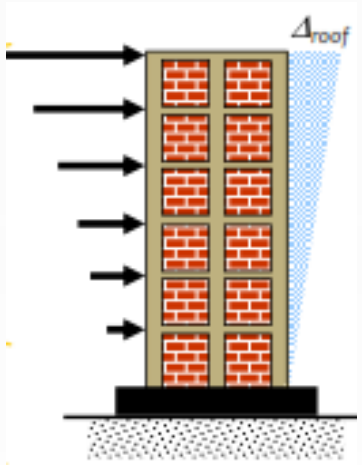
Wind

# Main Structural Concerns

| 01 | 02 | 03 | 04 | 05 | 06 | 07 |
|---|---|---|---|---|---|---|
| Stability | Strength | Deformation | Drift | Ductility | Energy Dissipation | Motion Perception |

**Traditional Design approach for Wind and Earthquake is different and is often in-consistent and opposing**

## **Wind** Load




**Depend on**
- Wind speed
- terrain
- topography of the location
- Force increases with height
- Geometry and exposed area

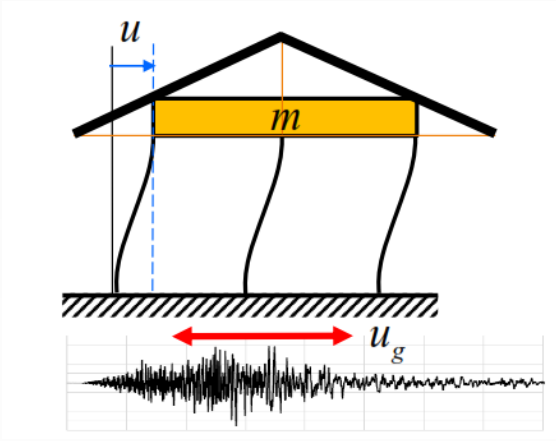
$$F_D = \frac{1}{2}\rho A C_D v^2$$

v

A

- Excitation is an applied pressure or force on the facade
- force will act mainly on exterior frames then transferred to floor diaphragms

## **Seismic** Load




**Depend on**
- focus of earthquake
- Shaking intesity
- ground conditions
- Mass and stiffness distribution

$$m\ddot{u} + 2\xi\omega m\dot{u} + m\omega^2 u = -m\ddot{u}_g$$

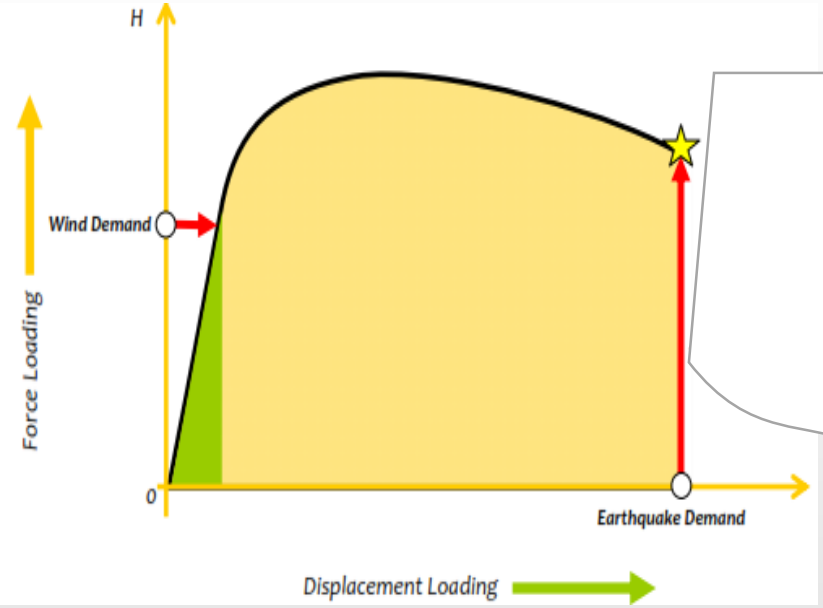
$\ddot{U}_g$

m

- Excitation is an applied displacement at the base
- force will be distributed along interior and exterior lateral load resisting elements

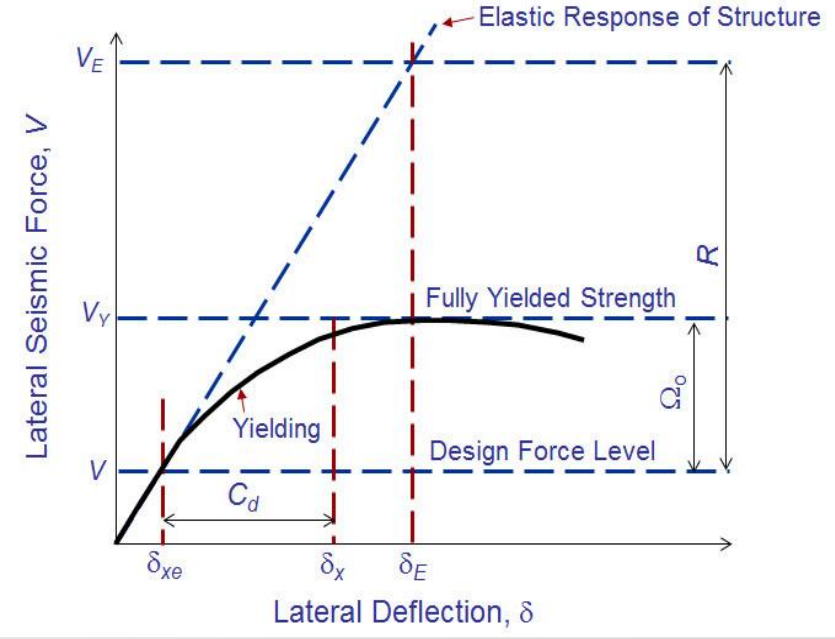
## Design for **Wind Load**

- For most buildings, dynamic wind response may be neglected
- Gust factor approach → predict dynamic response of buildings with reasonable accuracy
- Structures are designed to respond elastically under factored loads




## Design for **Seismic Effects**

- Structures are designed to respond inelastically under factored loads
- it is not economically feasible to design structures to respond elastically to earthquake ground motion

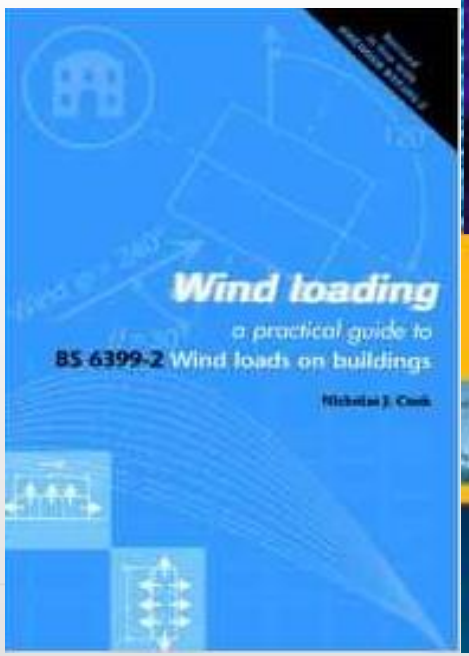


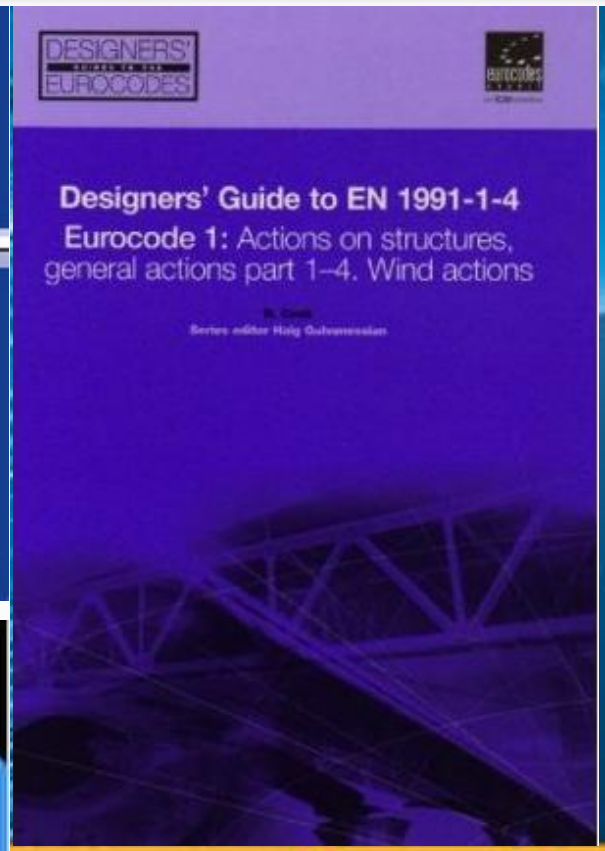
# Wind Codes

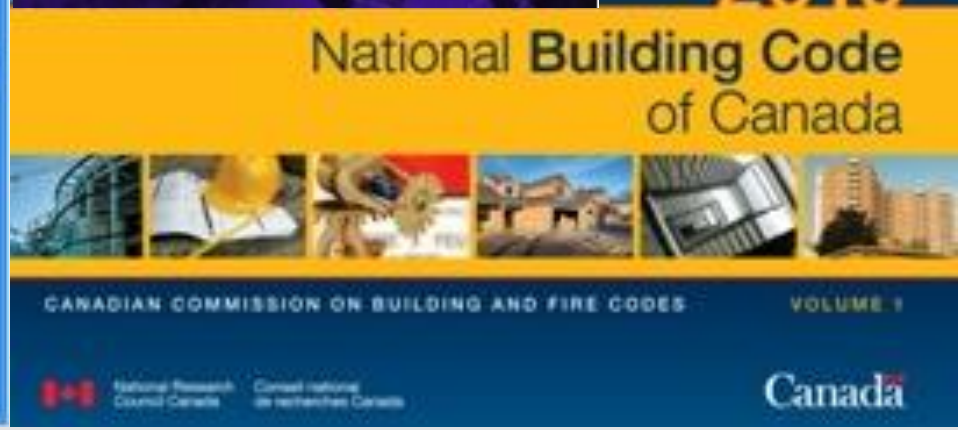
STANDARDS
NEW ZEALAND
PAEREWA AOTEAROA
Structural Design Actions
Part 2 – Wind actions
AS/NZS 1170.2:2011
STANDARDS
Australia

Minimum Design
Loads for Buildings
and Other Structures

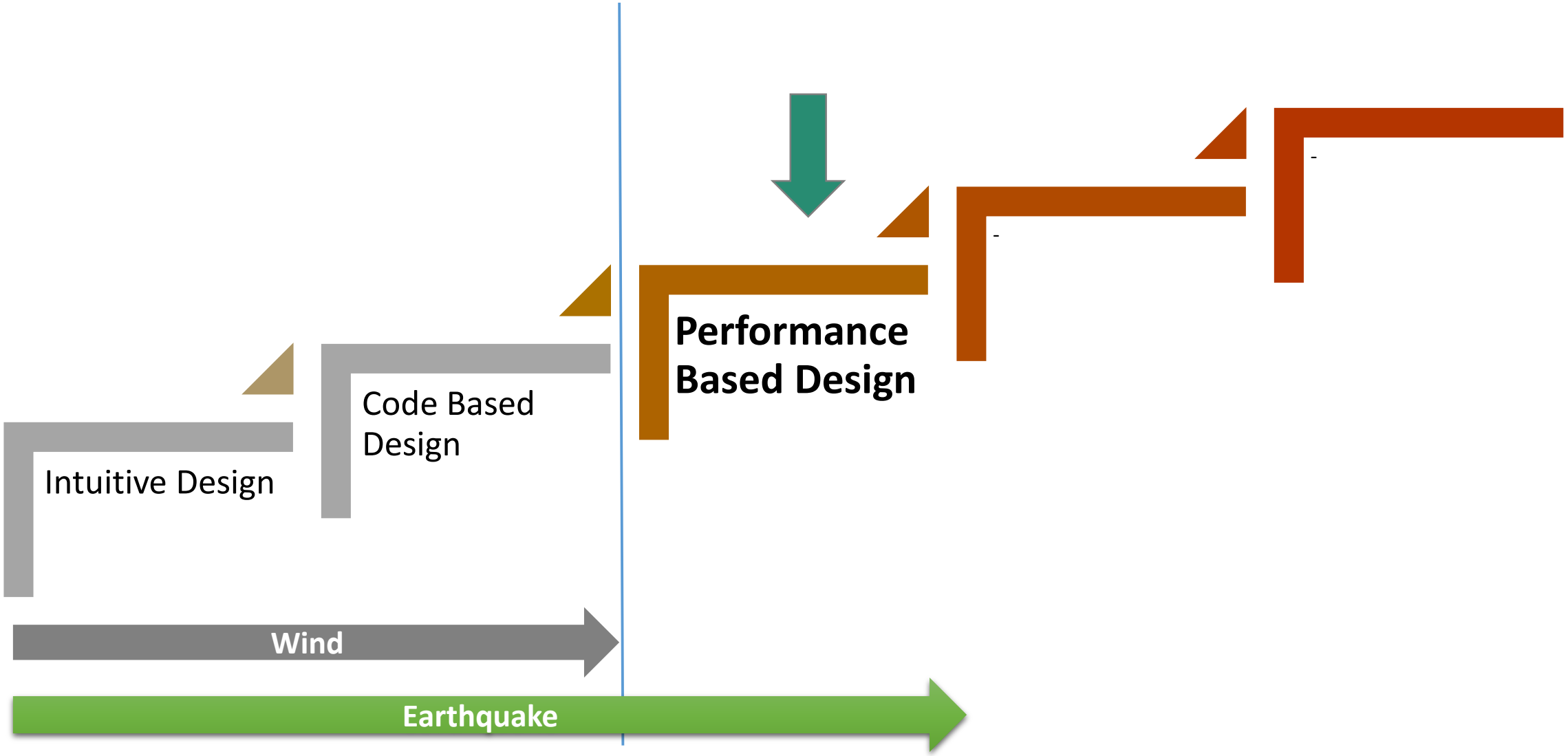
ASCE

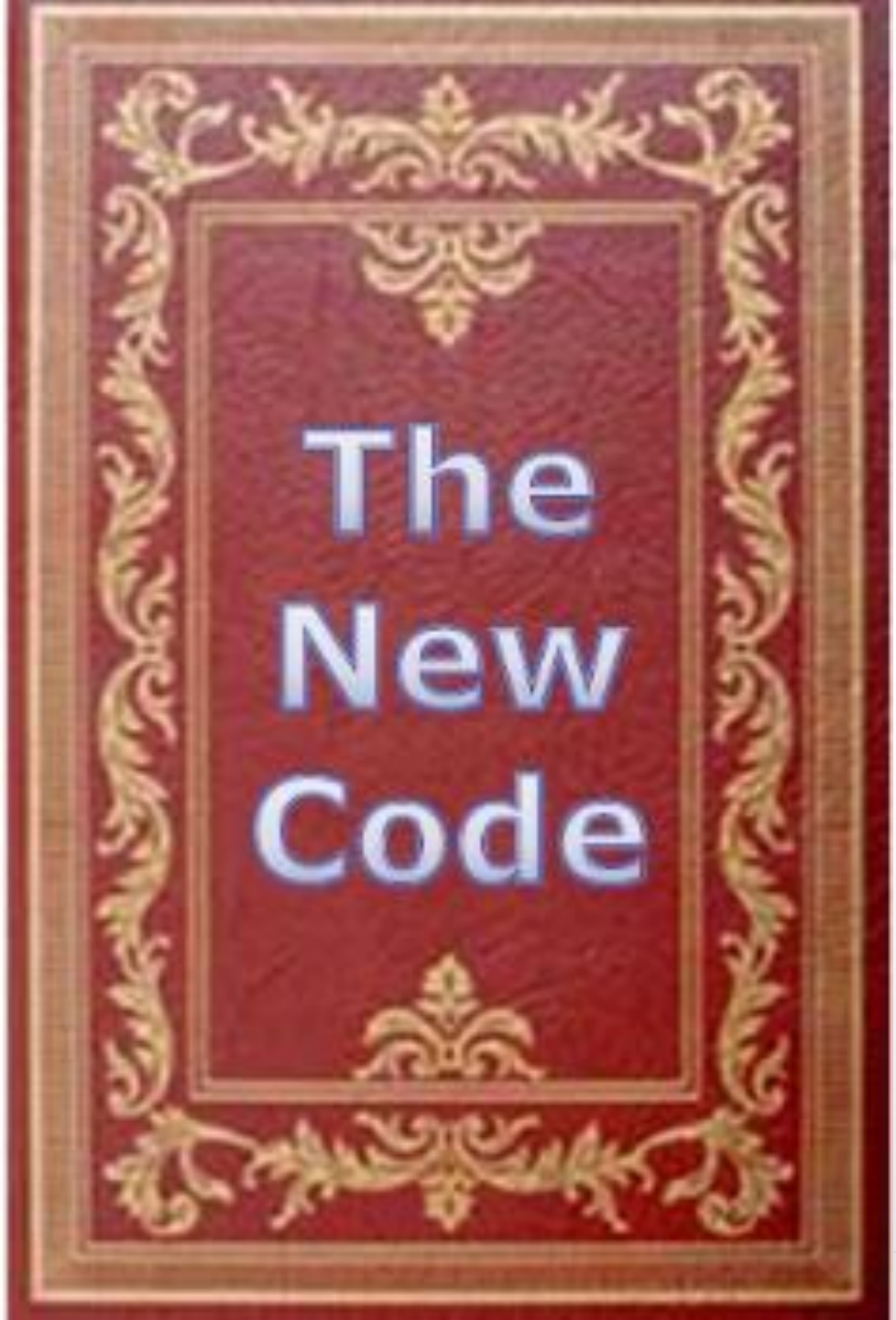

Wind loading
a practical guide to
BS 6399-2 Wind loads on buildings


DESIGNERS' GUIDE TO EUROCODES
Designers' Guide to EN 1991-1-4
Eurocode 1: Actions on structures,
general actions part 1–4. Wind actions


2010
National Building Code
of Canada
CANADIAN COMMISSION ON BUILDING AND FIRE CODES
VOLUME 1
Canada

# Design Approaches

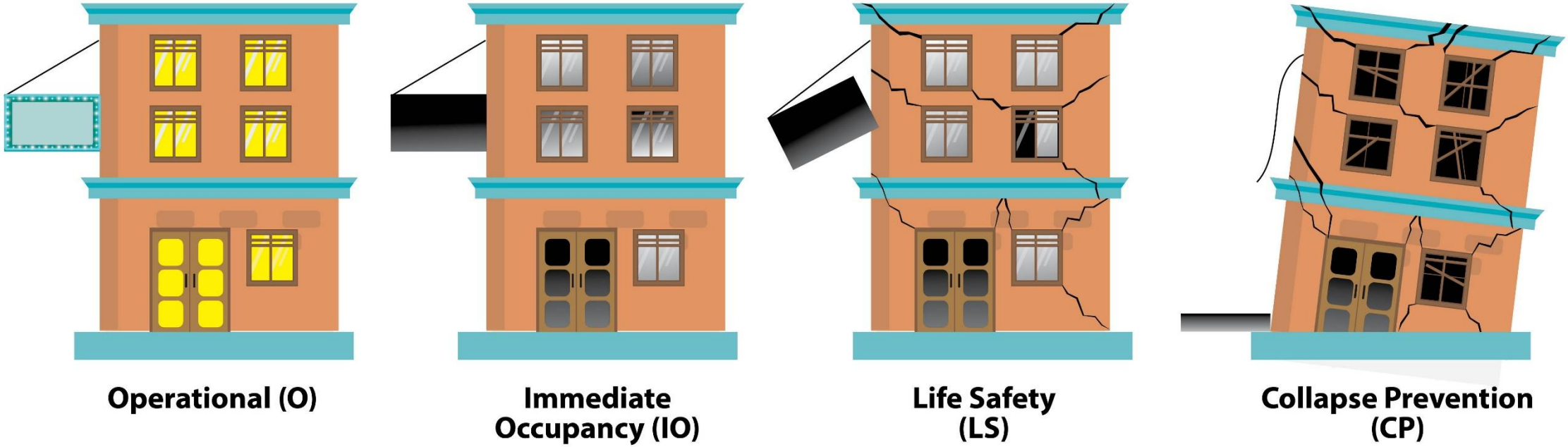





# Motivation for PBD in EQ

- Lack of explicit performance in design codes is primary motivation for performance based design
- Performance based methods require the designer to assess how a building is likely perform extreme events and their correct application will help to identify unsafe designs.
- Enables arbitrary restrictions to be lifted and provides scope for the development of innovative, safer and more cost-effective solutions

# Typical Performance Levels for Structures




**Based on FEMA 451 B**

# Explicit Performance Objective in PBD

Performance based design investigates at least two performance objectives explicitly

## Service-level Assessment

**Negligible damage with frequent hazards**

(Earthquake having a return period of about 50)

**Code's arbitrary "Design Level"**

## Collapse-level Assessment

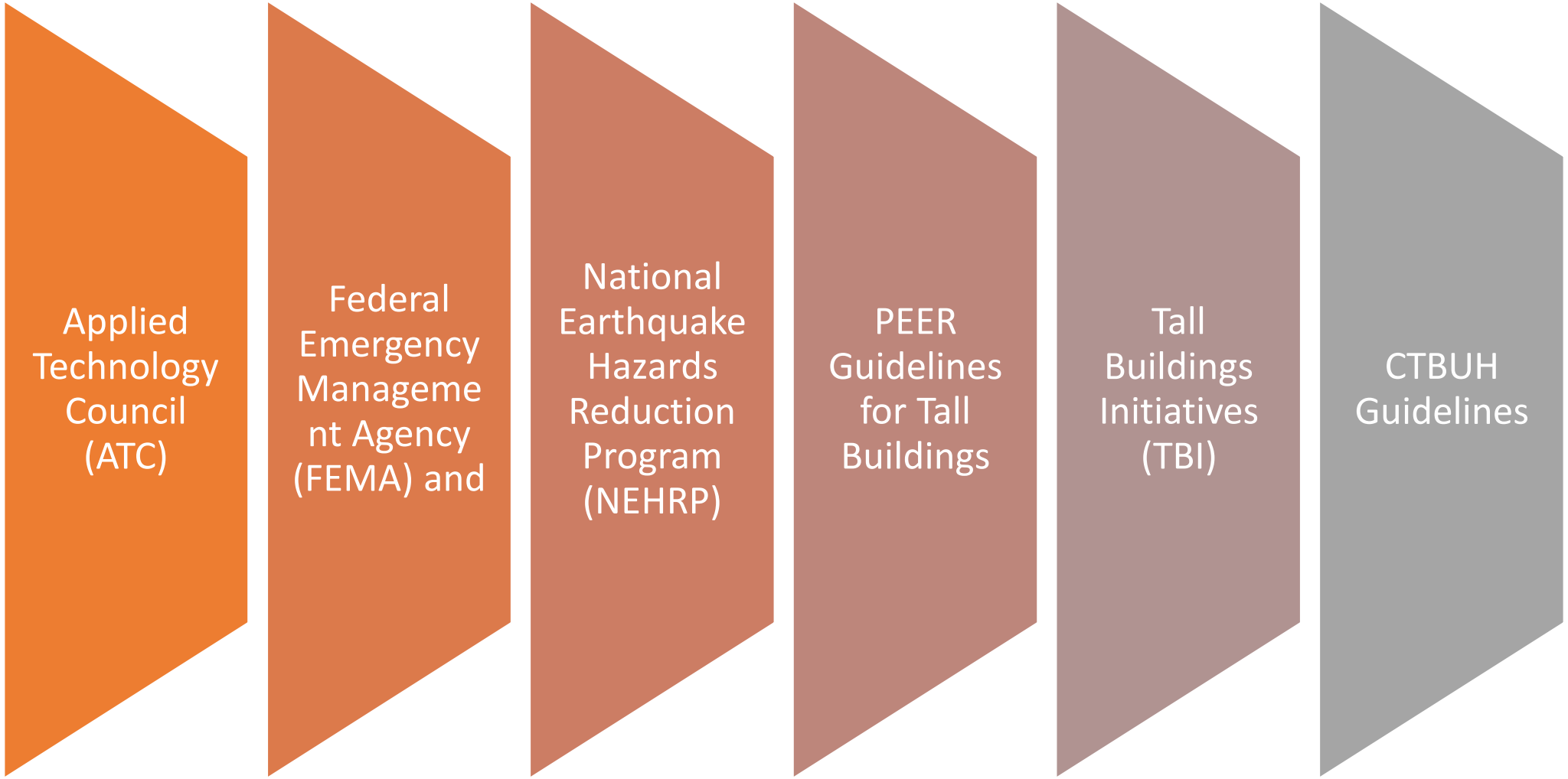
**Collapse prevention under extreme hazards**

(the largest earthquake with a return period of 2500 years)

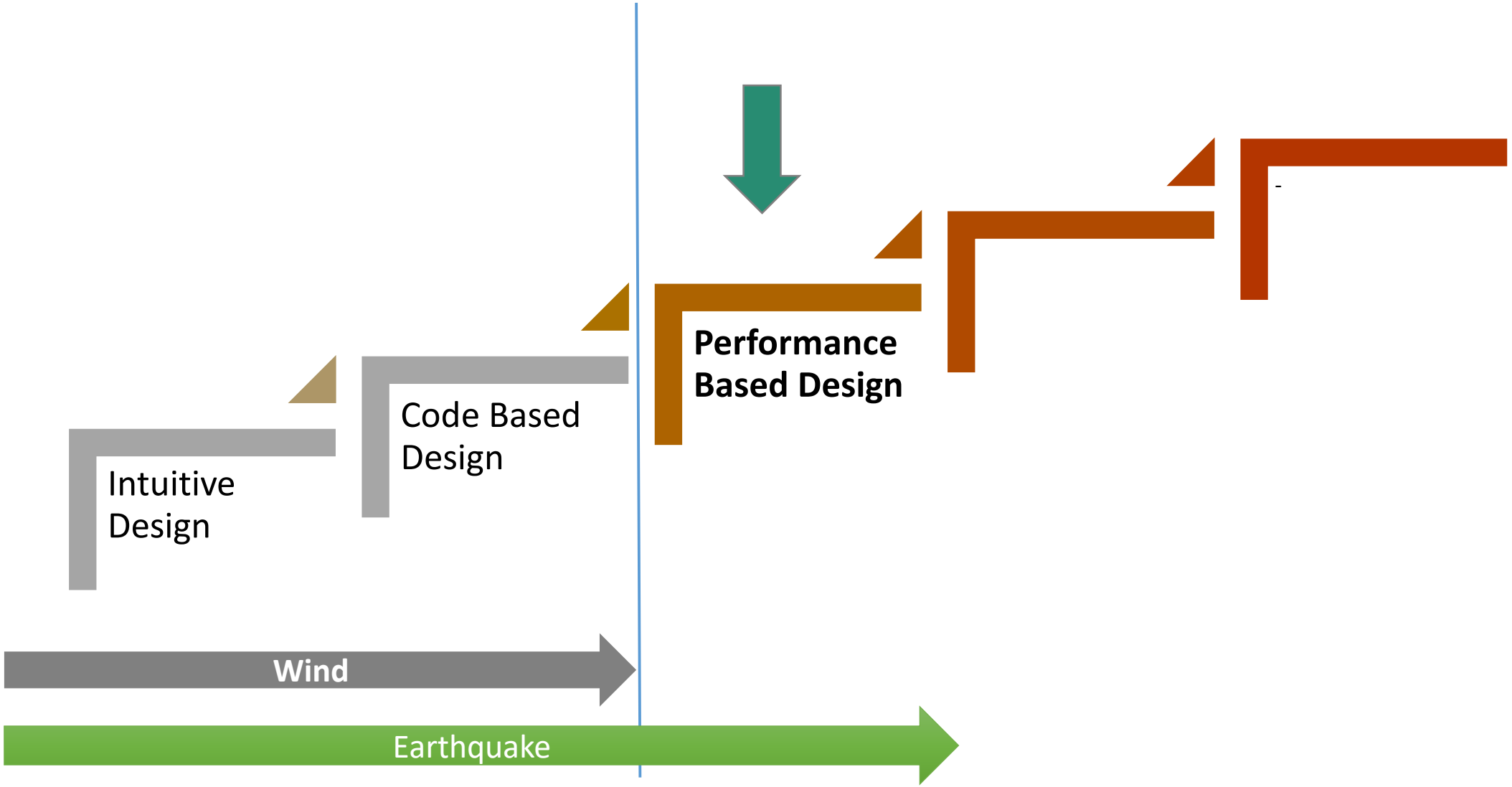
# Structural Performance Criteria in Seismic PBD

| Level of Earthquake | Seismic Performance Objective | Key Criteria |
|---|---|---|
| Frequent /Service Earthquake<br>43 yrs. Return Period<br>50% prob. of exceedance in 30 y | Limited Structural Damage | Story Drift is limited to 0.5% of Story height |
| Maximum Considered Earthquake (MCE)<br>2475 yrs. Return Period<br>2% prob. of exceedance in 50 y | Building is on a verge of collapse | Mean Peak Transient drift is limited to 3%<br>Max. Transient drift is limited 4.5%.<br>Mean and max. residual is 1% and 1.5% respectively. |

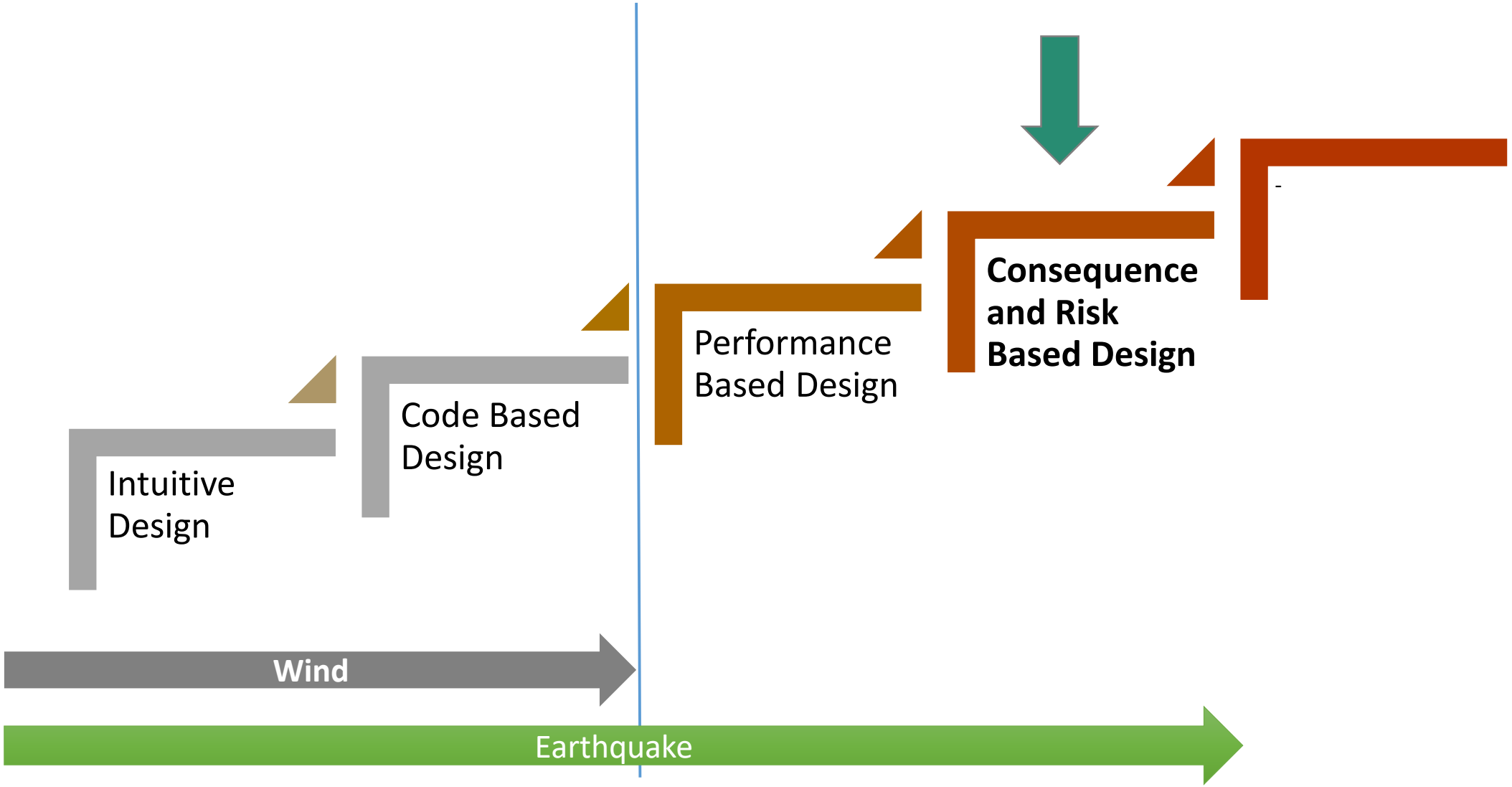
# Special Purposes Guidelines For PBD from USA



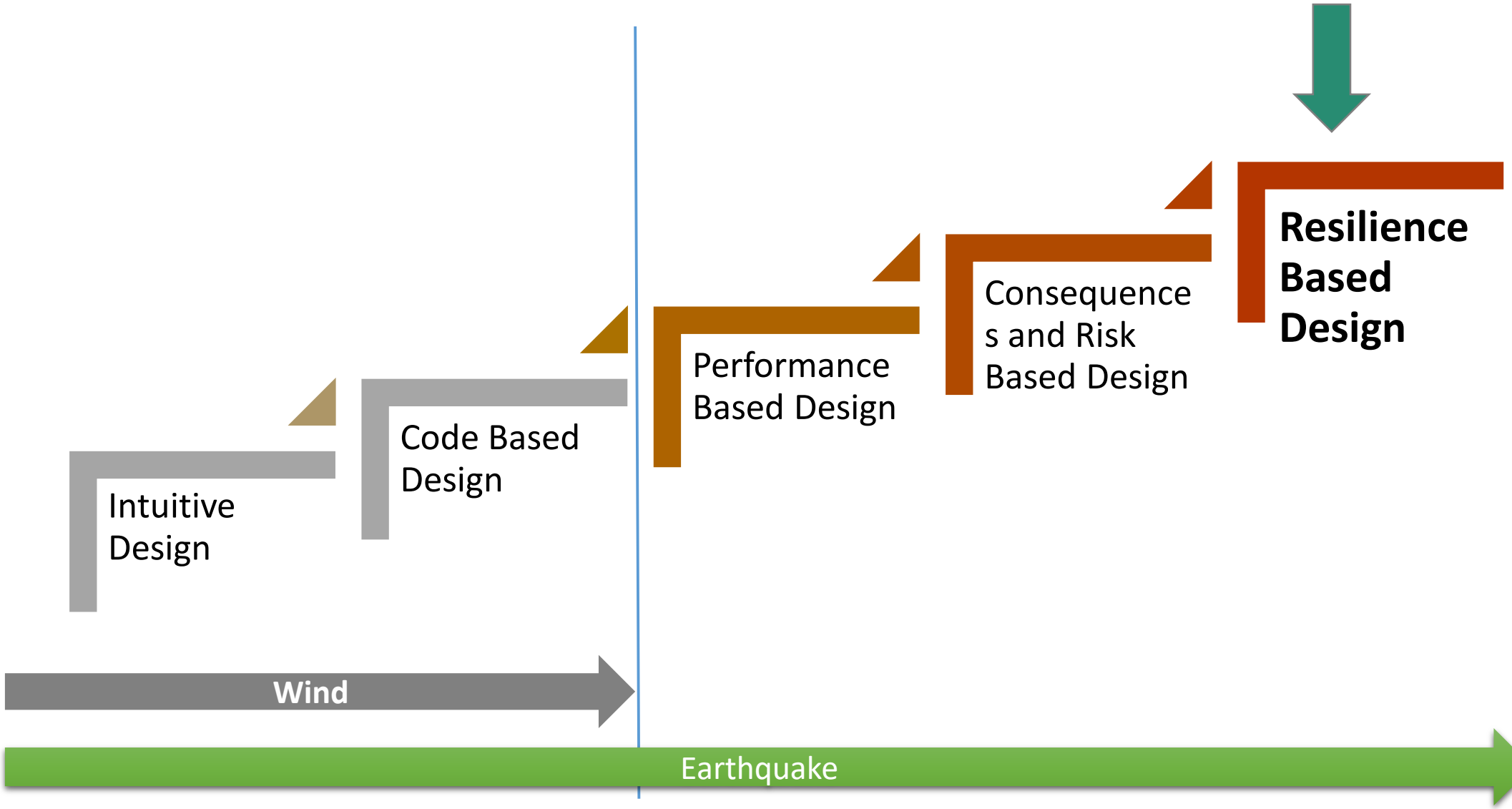
# Design Approaches



# Design Approaches



# Design Approaches



Green Buildings

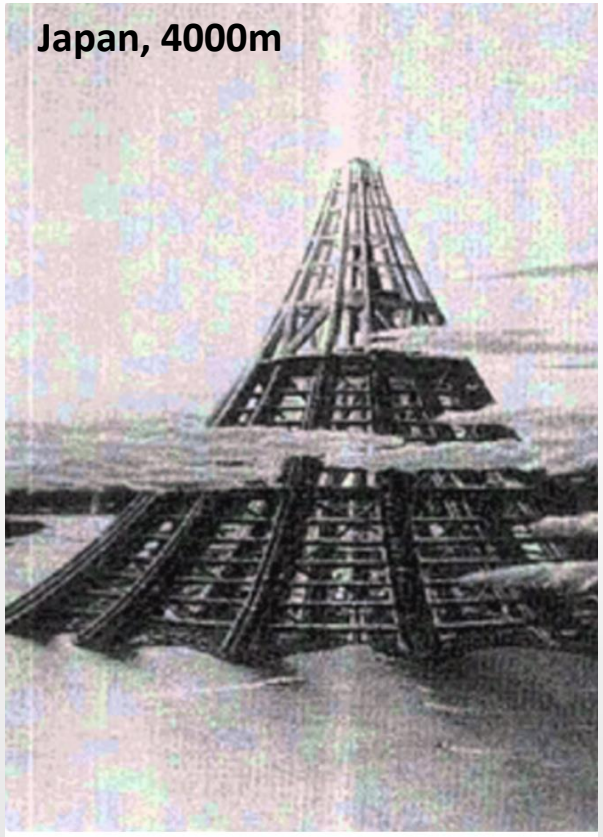
Resilient Buildings

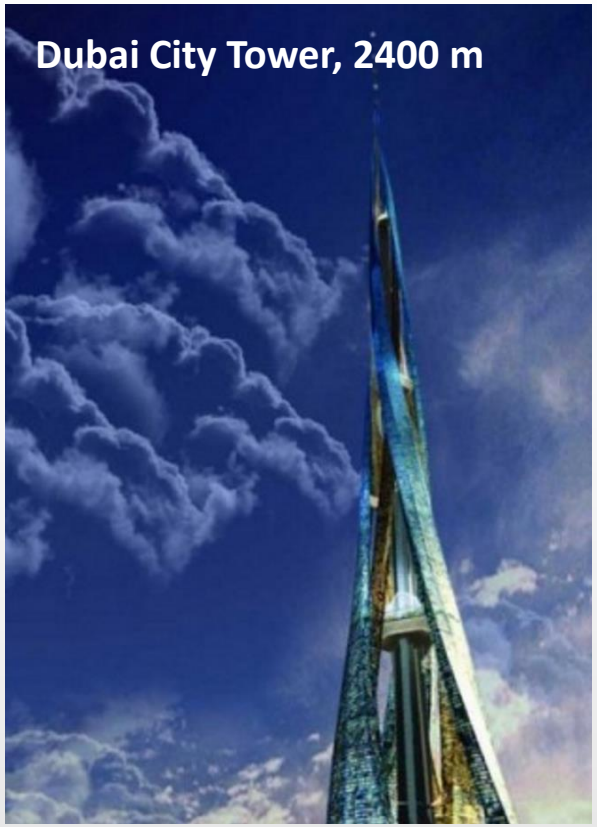
# Resilience-based Earthquake Design Initiative (REDi) Rating System for the Next Generation of Buildings

Main authors : Arup
Supported by USRC and many others

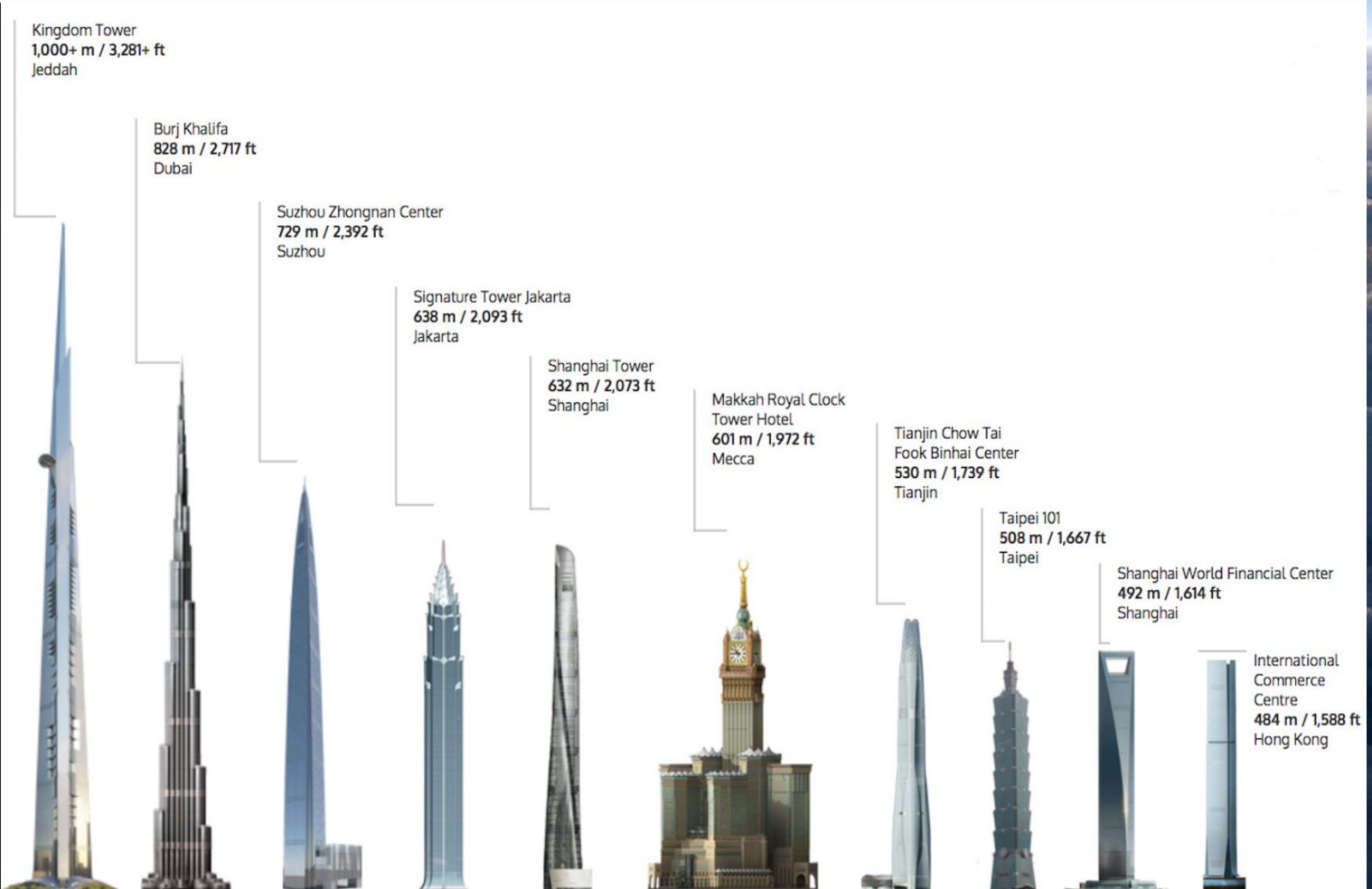
# Why PBD for Wind is Needed ?

# Dreams and Visions

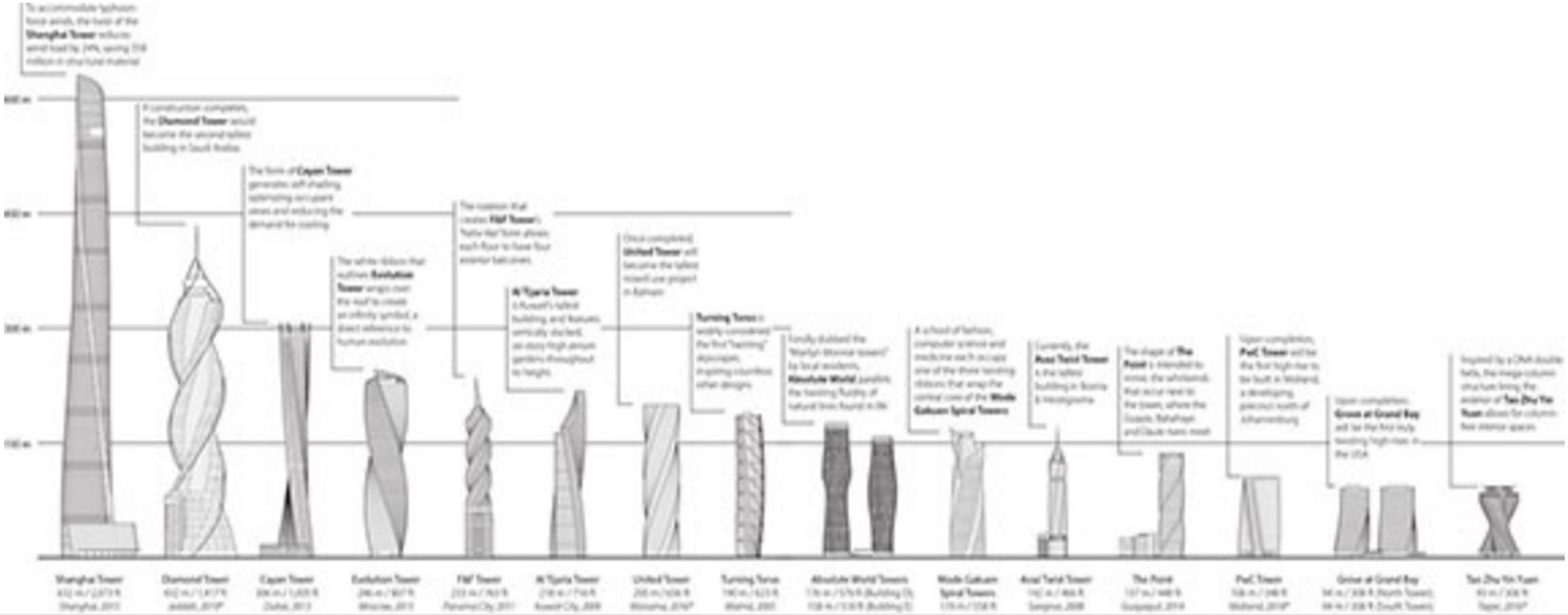


# They are getting taller



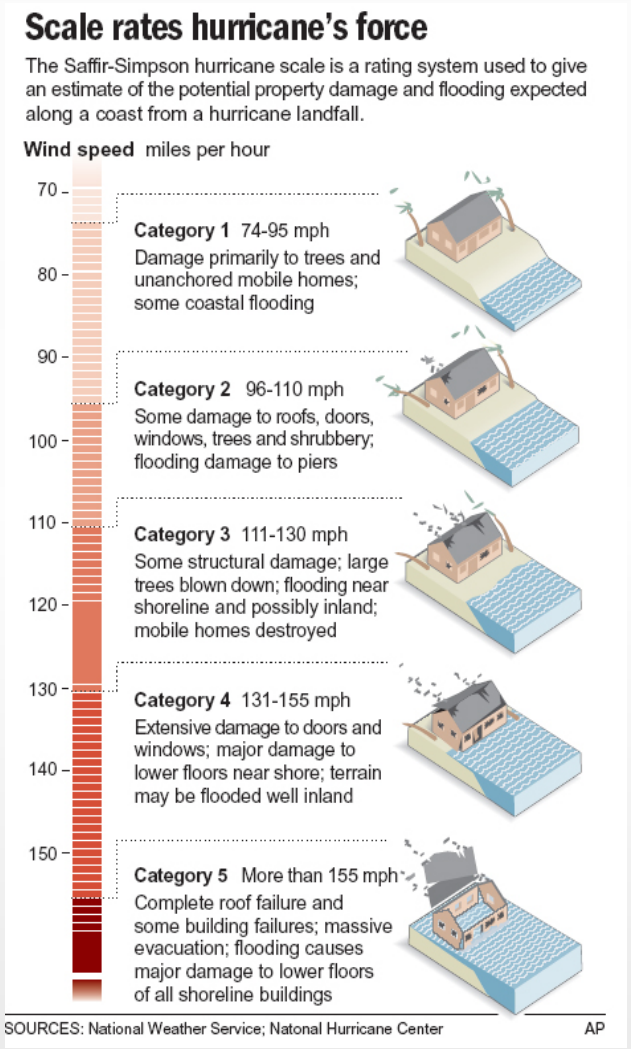
# They are getting complex

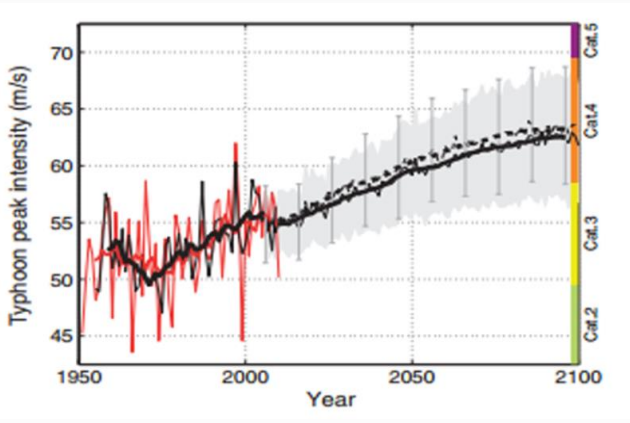


Source: CTBU Report, 2015

# Climate Change may effect future wind hazard level

| Before Climate Change | After Climate Change |
|---|---|
| Common Event | Common Event |
| Common Event | Common Event |
| Occasional Event | Occasional Event |
| Rare Event | Occasional Event |
| Very Rare Event (Might never happen) | Occasional Event |




**Will there be a Category 6?**

# Wind Codes – What do they miss

| Give | Miss |
| --- | --- |
| • Wind load factors to convert certain wind speed to different return period wind speed<br>• Standard Pressure Coefficient<br>• Cover background and Resonant force thru Gust Factor<br>• Design for linear, static, elastic response | • Most do not give explicit Structure Performance under different level of wind speed based on it's probable occurrences<br>• Do not explicitly incorporate Wind-tunnel test outcome<br>• They differ from each other in concept, factors, outcome<br>• Nonlinearity, dynamics, inelasticity |

# Most Codes Differ – Which one is right?

**TABLE 2. Calculated Gust Factors for International Codes & Standards**

| Code/Standard | | ASCE7-95 | Australia* | Eurocode | Canada | AIJ |
|---|---|---|---|---|---|---|
| Gust Duration | | 3 sec | 3600 sec | 600 sec | 3600 sec | 600 sec |
| Reference Velocity | $V_4$ | 1.05 | 2.95 | 1.78 | 2.96 | 2.20 |
| | $V_3$ | 1.02 | 2.87 | 1.76 | 2.78 | 2.12 |
| | $V_2$ | 1.01 | 2.83 | 1.71 | 2.70 | 2.08 |
| | $V_1$ | 0.975 | 2.80 | 1.72 | 2.61 | 2.05 |

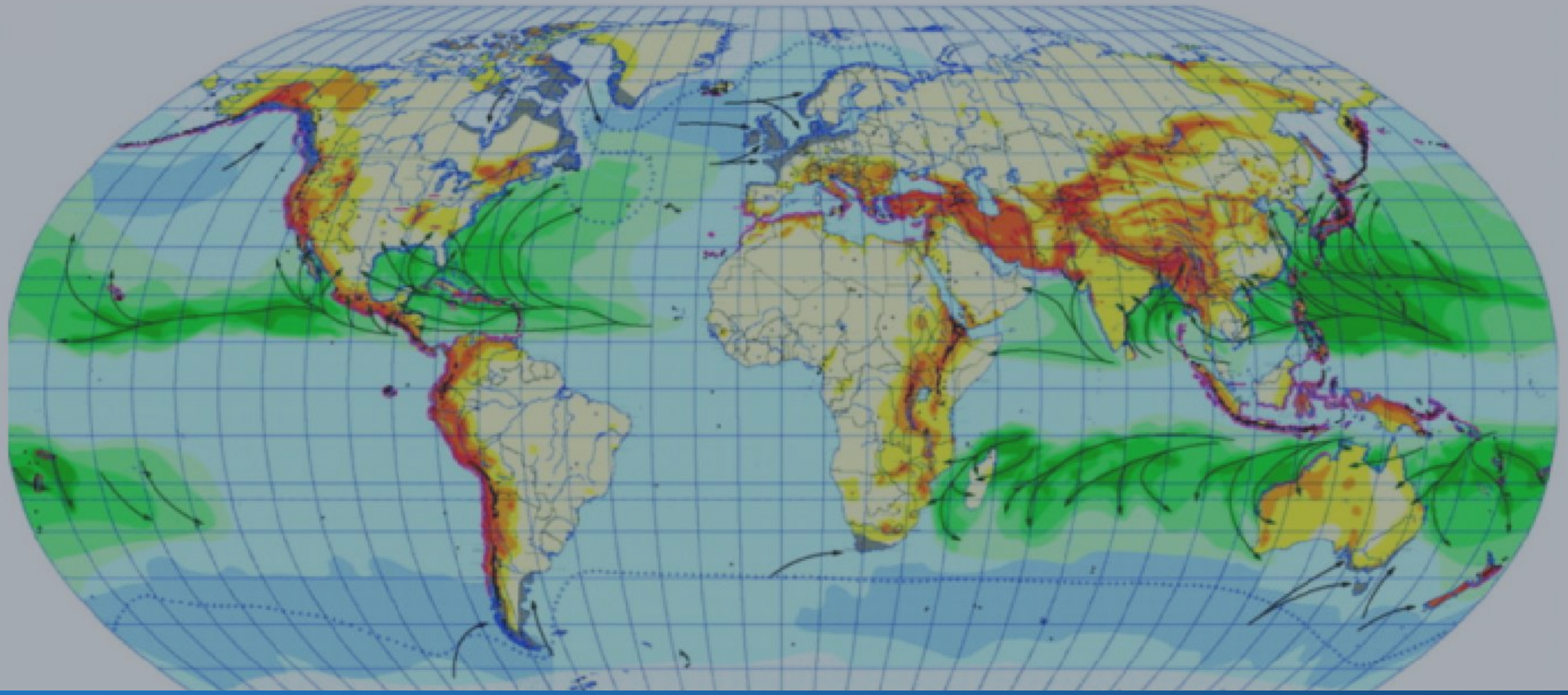
See Table 1 for the reference velocity used for each standard.
*Australian Standard uses mean hourly wind speed for calculation of loads.

**TABLE 3. Comparison of Calculated Peak and RMS Alongwind Accelerations from International Codes & Standards with Wind Tunnel Data.**

| | Ref Velocity [mph] | ASCE7-95 | Australia | Eurocode | Canada | AIJ | Wind Tunnel Data |
|---|---|---|---|---|---|---|---|
| Alongwind Peak Acceleration [milli-g's] | 90 | 22.30 | 31.65 | 21.78 | 28.80 | 19.84 | 21.59 |
| | 80 | 15.76 | 24.36 | 15.46 | 20.19 | 14.16 | 15.05 |
| | 75 | 13.70 | 21.14 | 12.79 | 16.49 | 11.77 | 12.81 |
| | 70 | 10.34 | 18.18 | 10.45 | 13.33 | 9.66 | 10.71 |
| Alongwind RMS Acceleration [milli-g's] | 90 | 5.90 | 8.73 | 6.81 | 7.68 | 6.04 | 6.17 |
| | 80 | 4.16 | 6.72 | 4.86 | 5.39 | 4.31 | 4.30 |
| | 75 | 3.62 | 5.83 | 4.03 | 4.41 | 3.58 | 3.66 |
| | 70 | 2.73 | 5.01 | 3.30 | 3.57 | 2.94 | 3.06 |

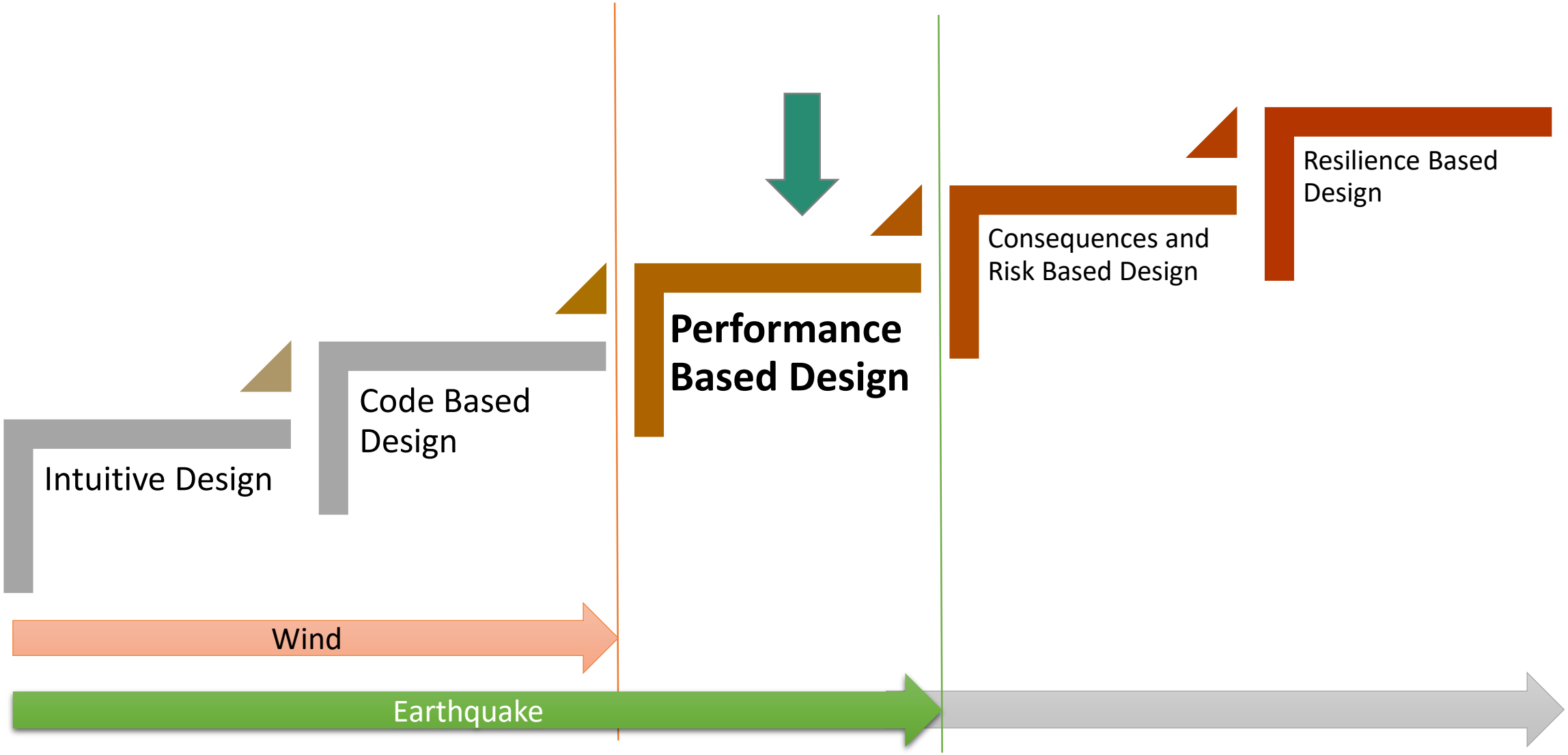
*For the wind tunnel data, the alongwind peak acceleration is estimated by multiplying the alongwind RMS acceleration by the peak factor, assumed to be 3.5.

*Dynamic Wind Effects: A Comparative Study of Provisions in Codes and Standards with Wind Tunnel Data, T. Kijewski1 A. Kareem, https://www3.nd.edu*

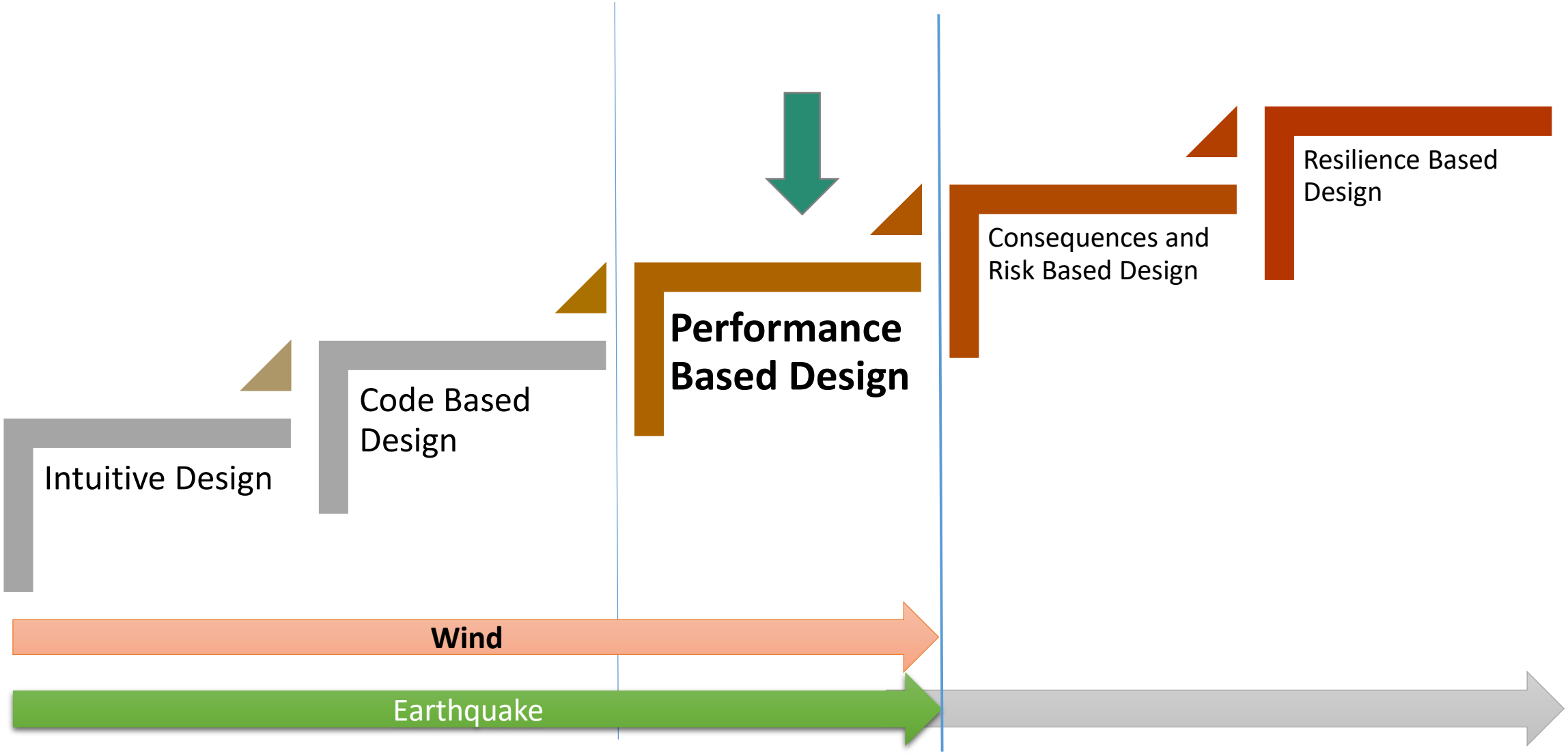


# Why Integrated PBD for Earthquake and Wind?

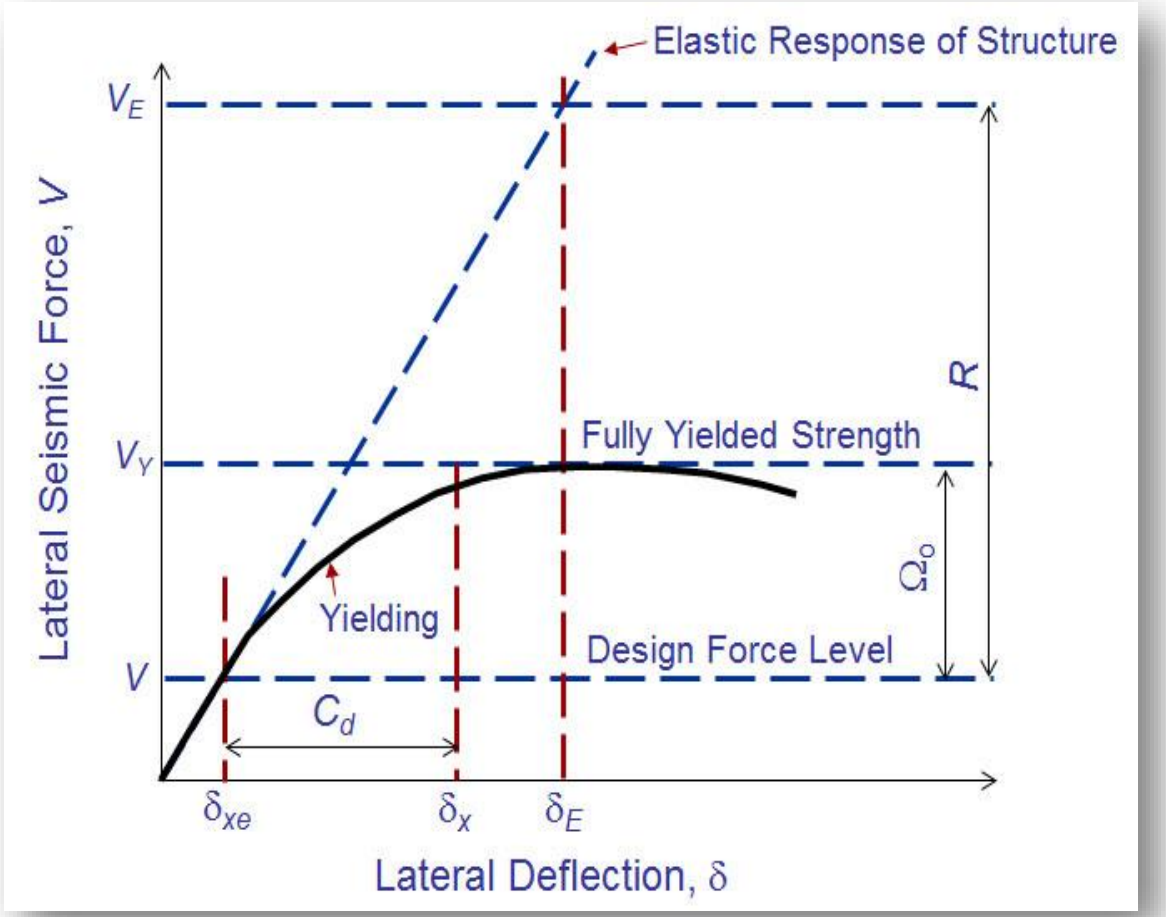
# Design Approaches

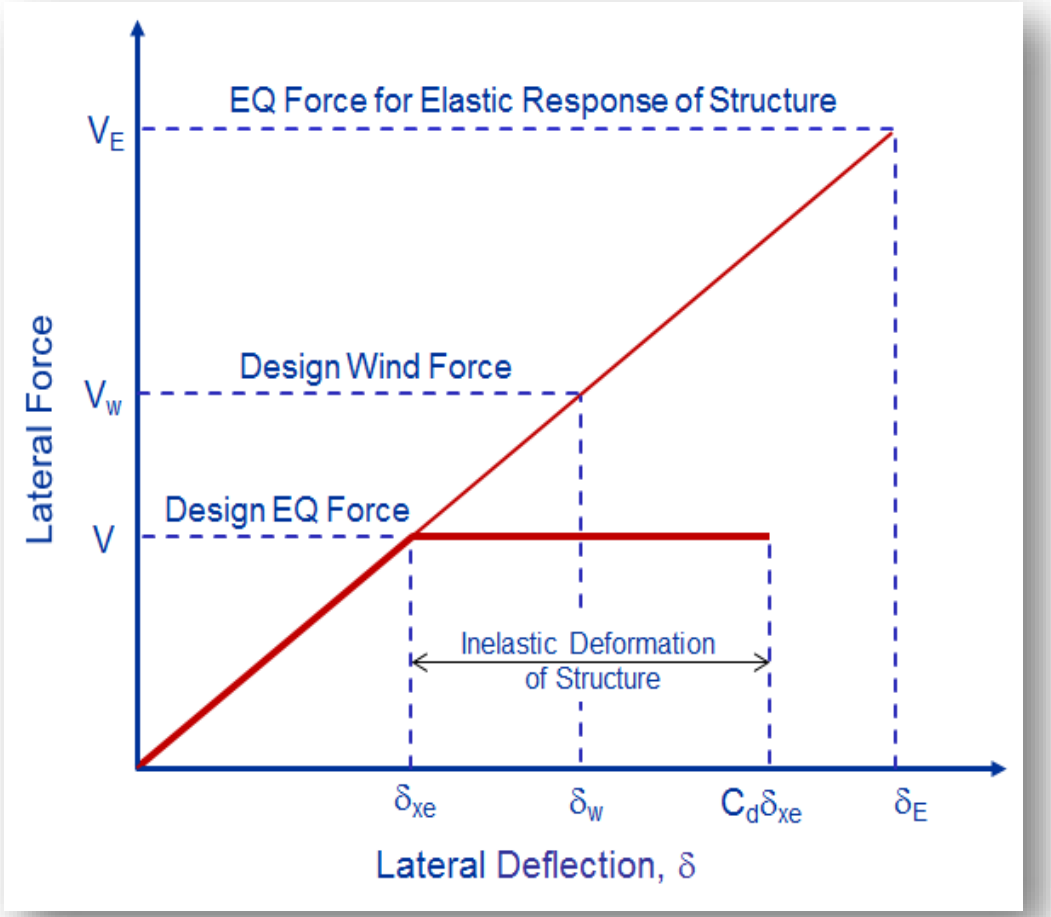


# Design Approaches

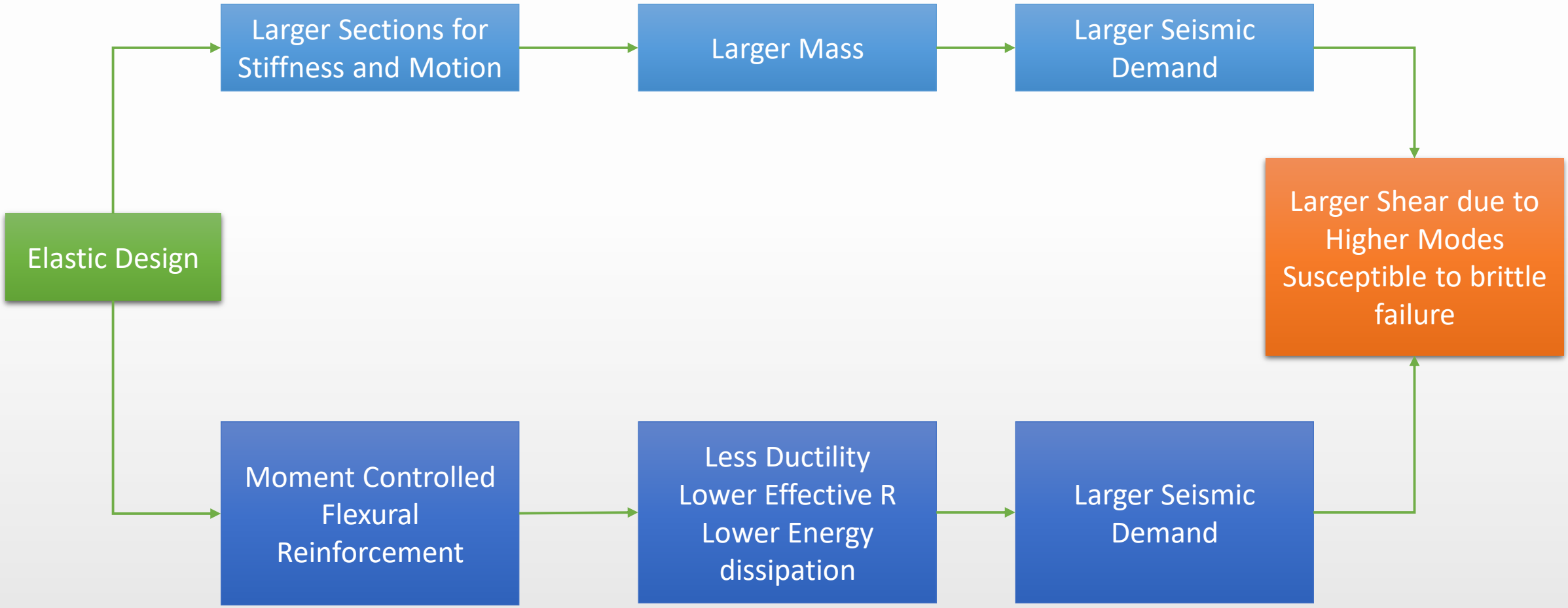


# Seismic Demand and Design may Depend on Wind Demand and Design



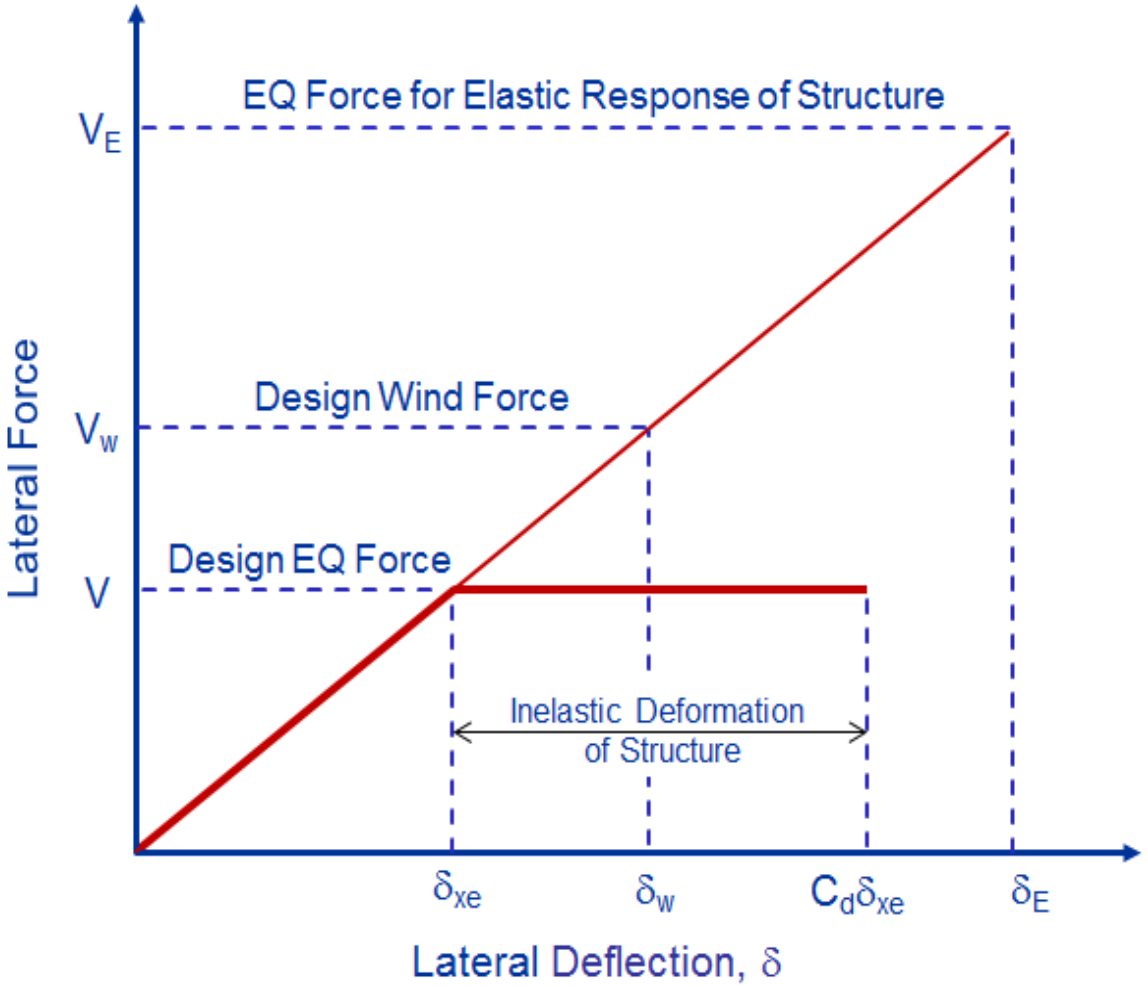



# Linear-Elastic Wind Design Effects Seismic Performance



# The Effect of Wind on Seismic Performance

- The calculated wind resistant demand can be higher than the seismic design demand (RSA) due to reduction of elastic design load by force reduction factor (R)
- The actual seismic demands can be higher than both wind and design seismic demand
- Demands in the higher modes in inelastic range are not reduced by the same "R" factor which is intended in the RSA procedure
- Wind Moment is 1st Mode type
- Seismic shear is Higher mode based

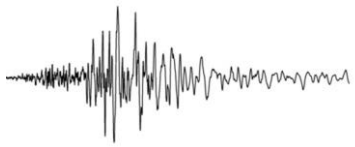


**Extreme Events** should be handled Consistently

# Earthquakes, Wind, Blast, Progressive Collapse, Impact

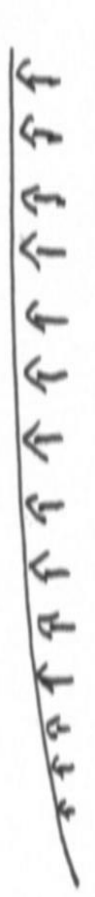
# Earthquake and Wind PBD are Compatible!

**Earthquake**



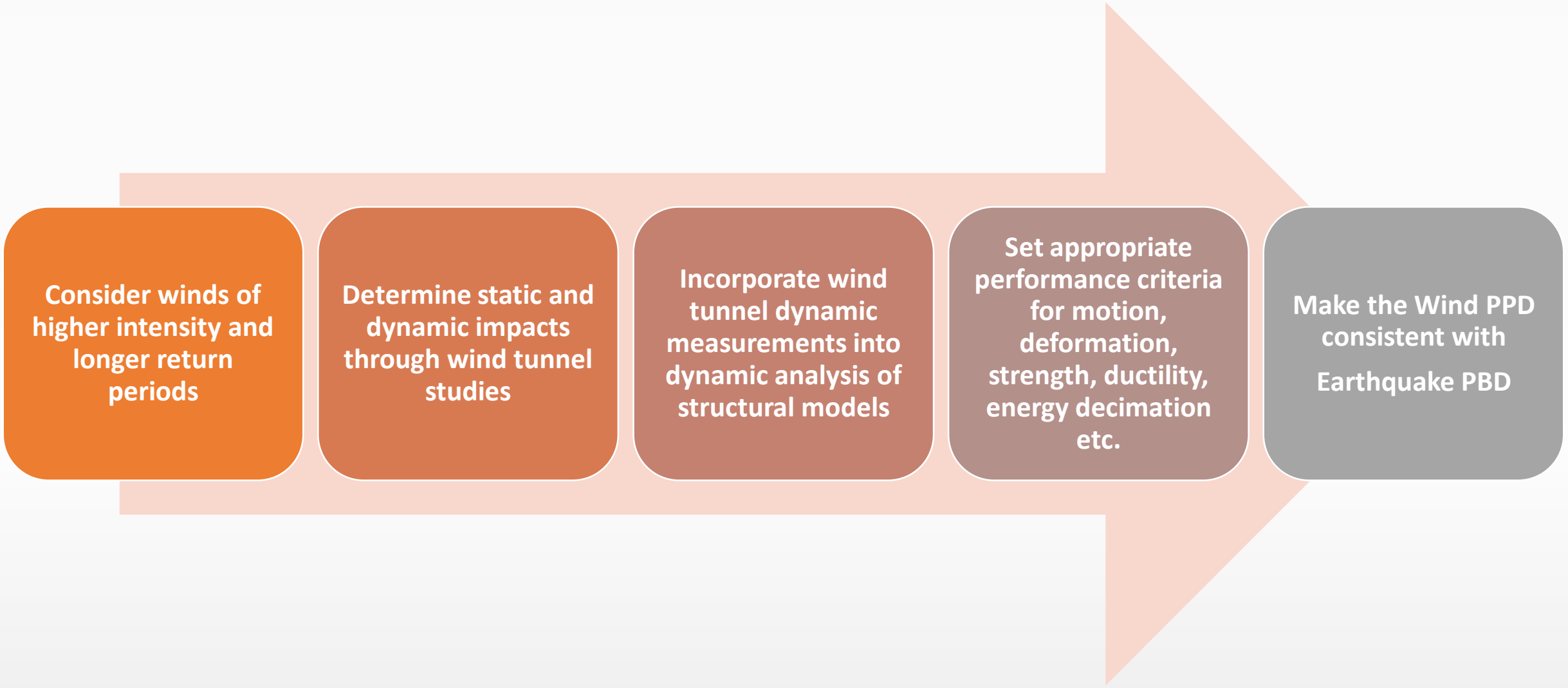
- Site specific Seismic Hazard Study
- Various Earthquake levels SLE, DBE, MCE etc
- Hazard Response Spectrum
- Ground Motion Time History

- Site specific Climate Analysis
- Various Wind Return period and Velocities
- Wind Force in Frequency Domain
- Wind Tunnel Pressure in Time Domain



**Wind**

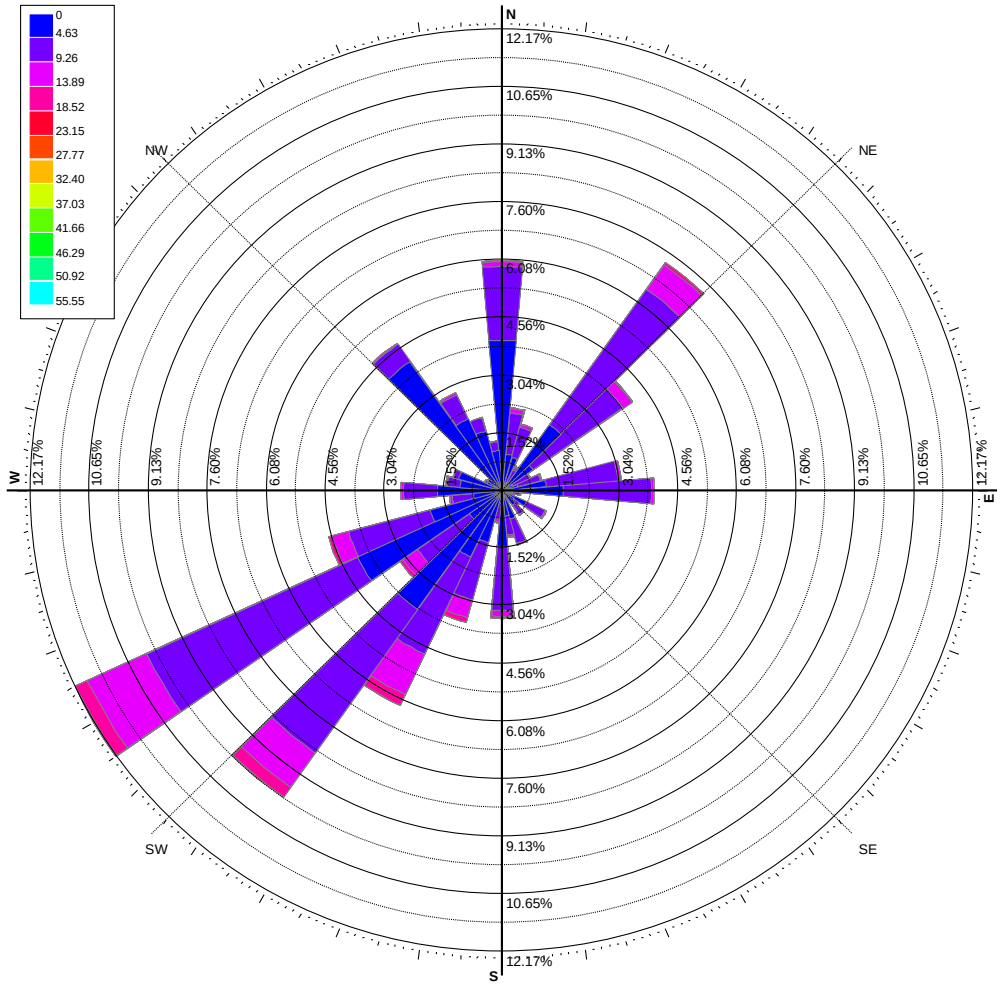
# What is needed and How it can be done?




# Possible Way forward

# Wind Climate Analysis

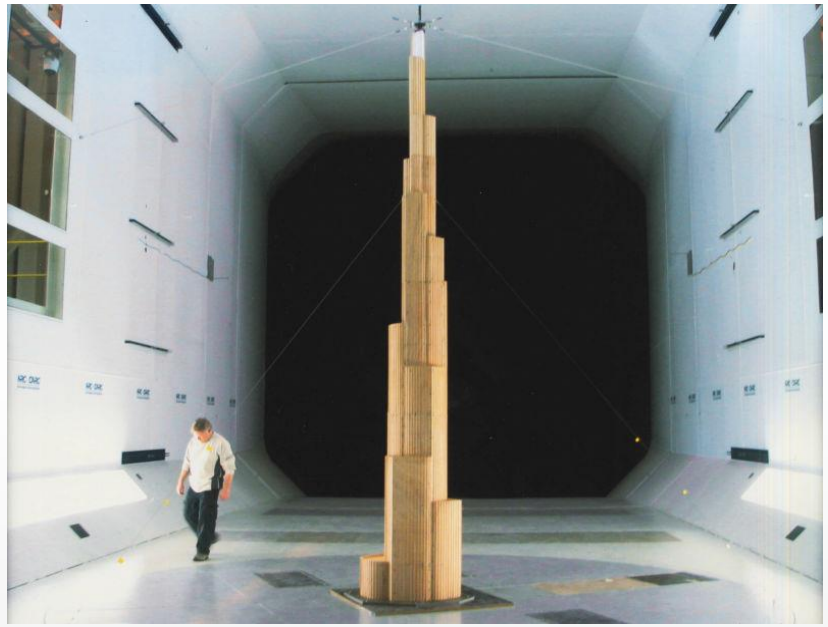
- The wind climate model is derived from the analysis of meteorological data used in wind tunnel model
- Wind model is combined with terrain analysis  to get target wind properties for the wind tunnel test.
- Several return periods and intensities are considered



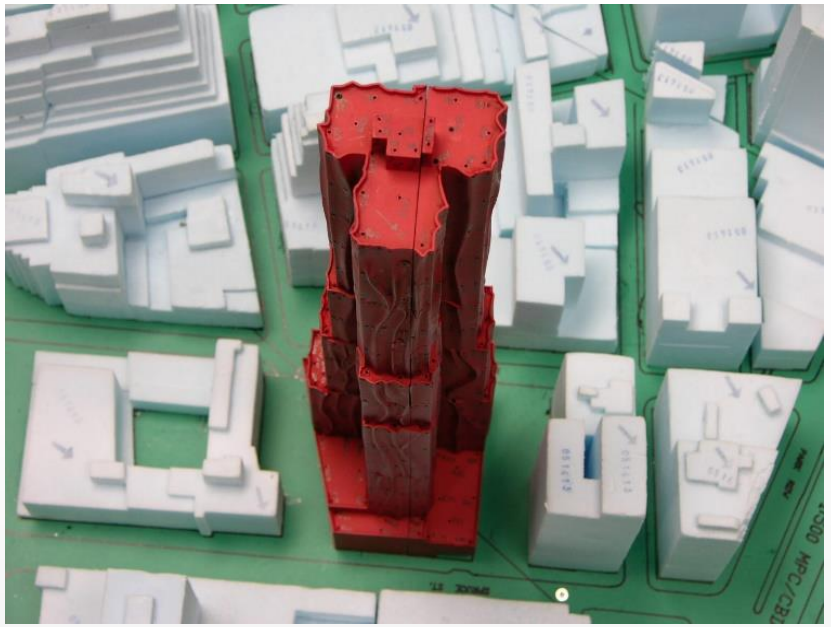



AIT Solutions

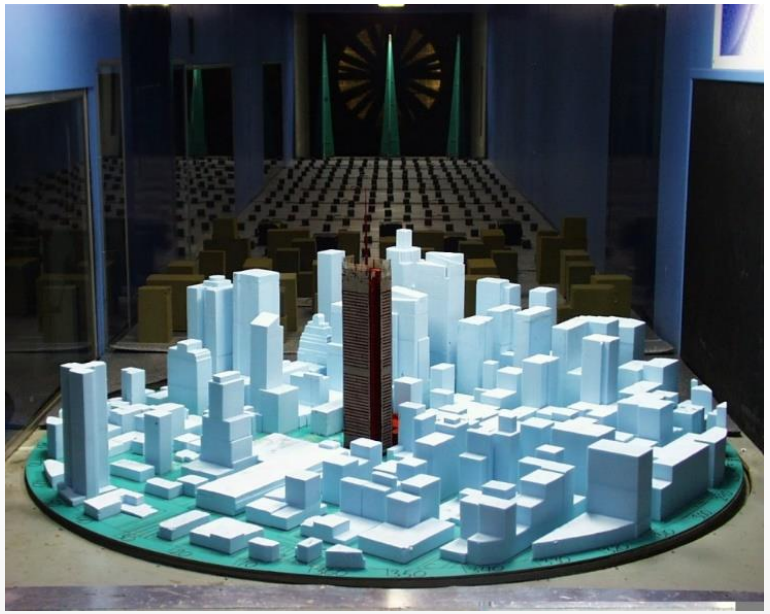
# Wind Test Models



**Force balance model,**



**Pressure model**



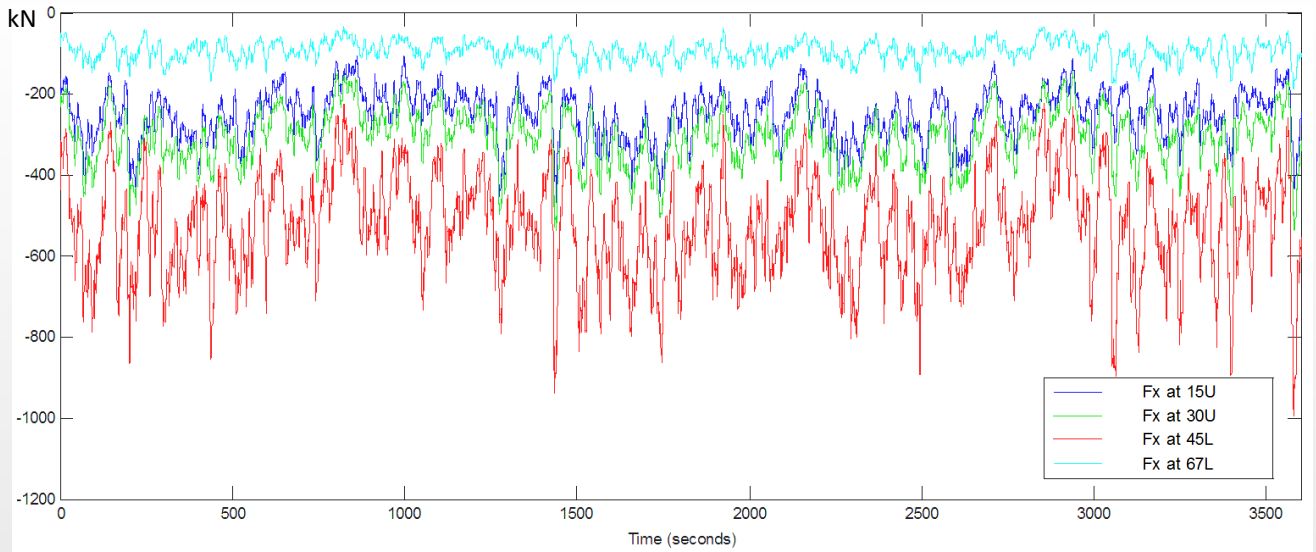
**Surrounding model**

*(Images based on RWDI facilities)*

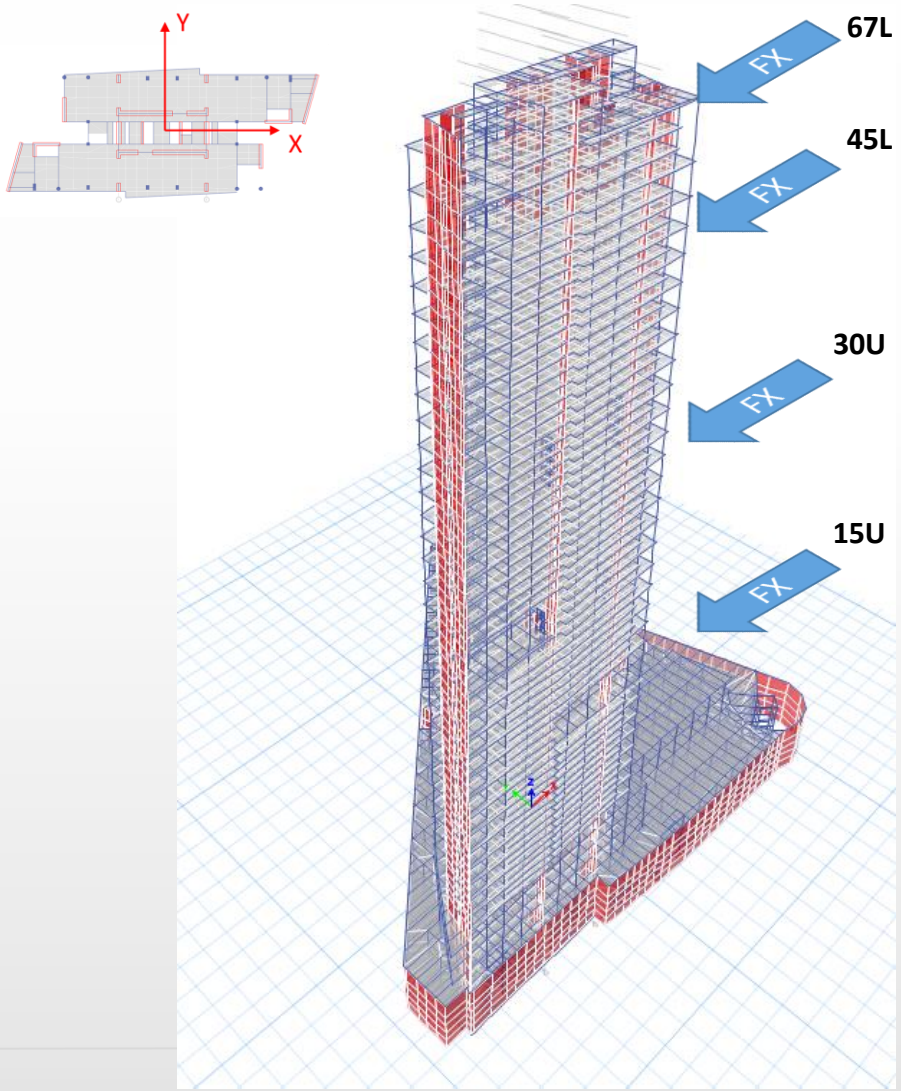
# Apply Wind as Dynamic Effect

Wind load obtained from wind tunnel test can be either point loads or area pressure loads depending on which technique being used.

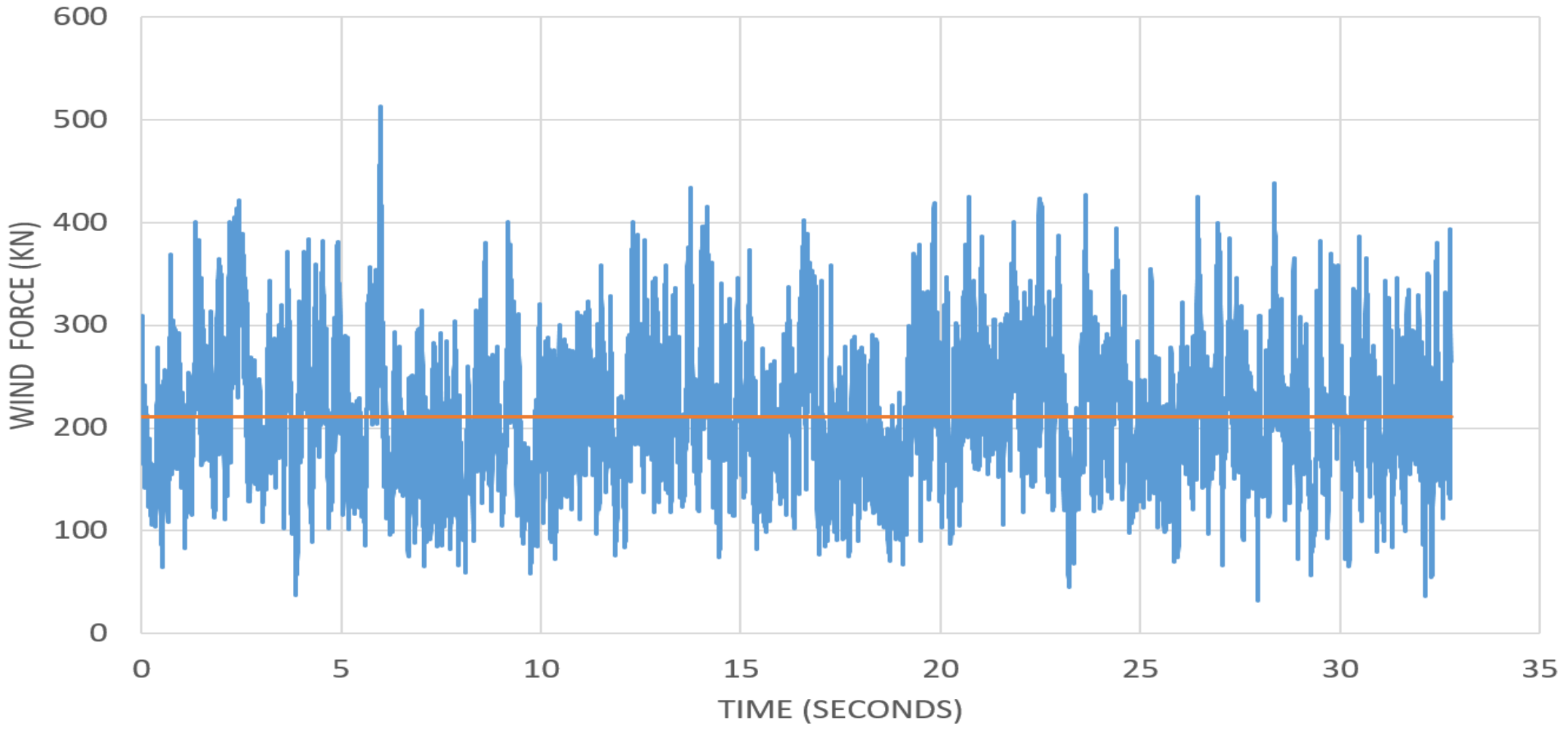
- Point loads
- Area pressure loads




**1 hour span of time history point loads at different elevations**

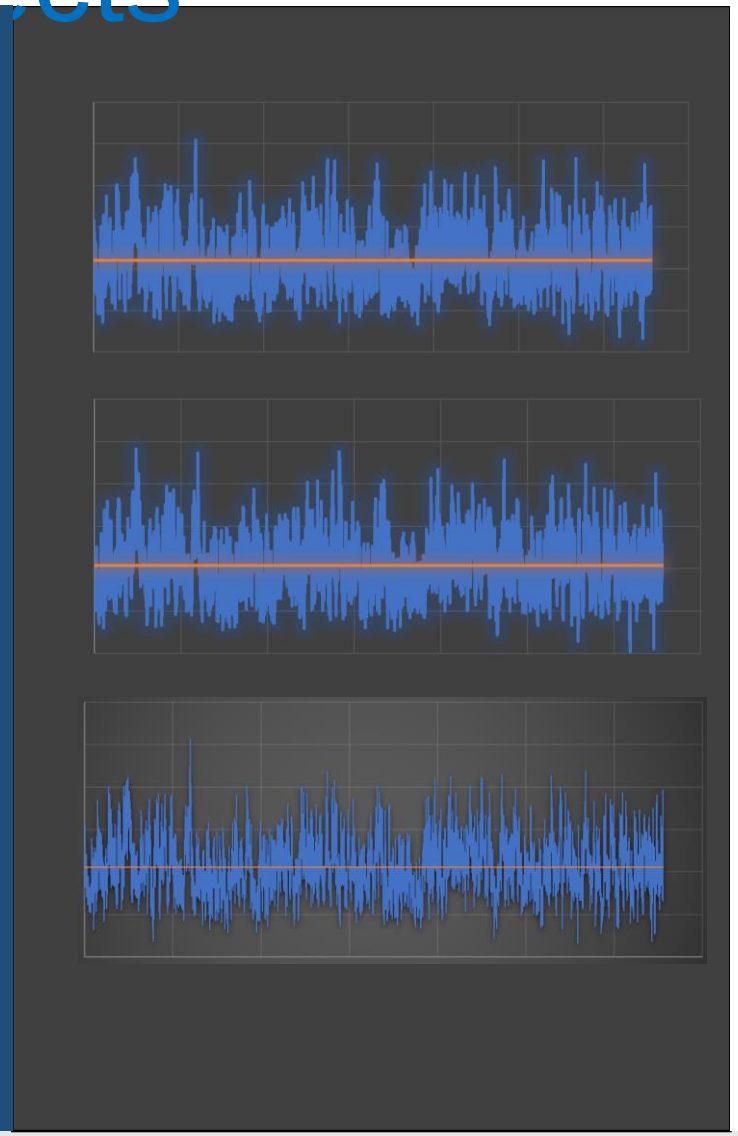


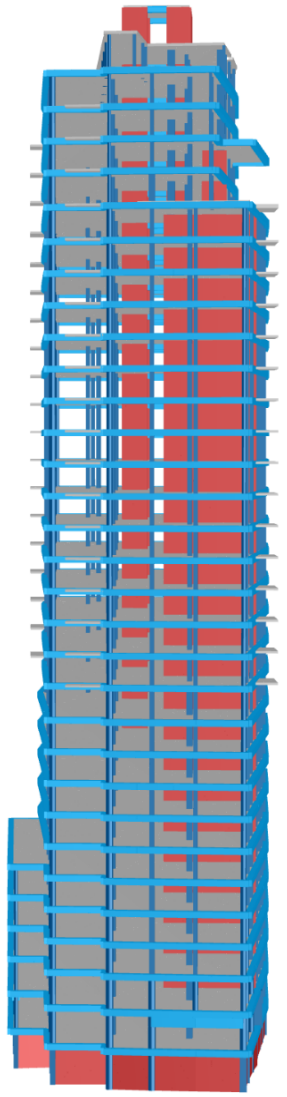
# The Wind Force Fluctuations and Mean Force



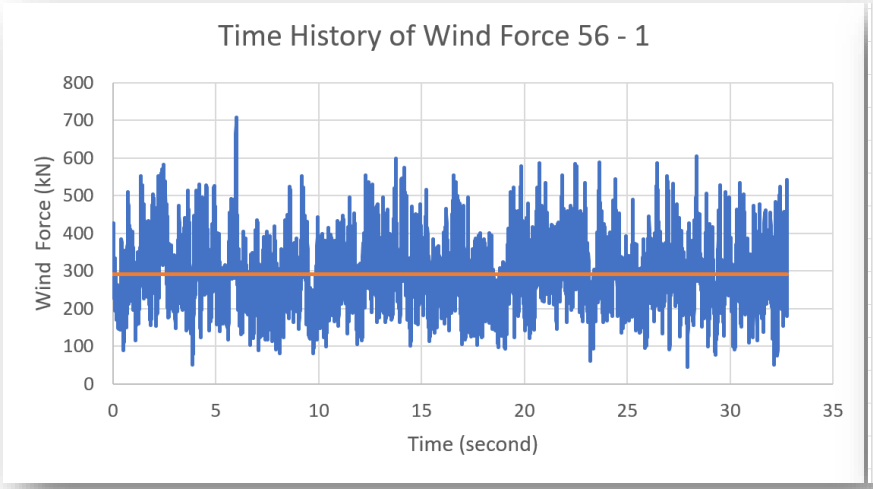
# Wind Pressure Variation and Dynamic effects

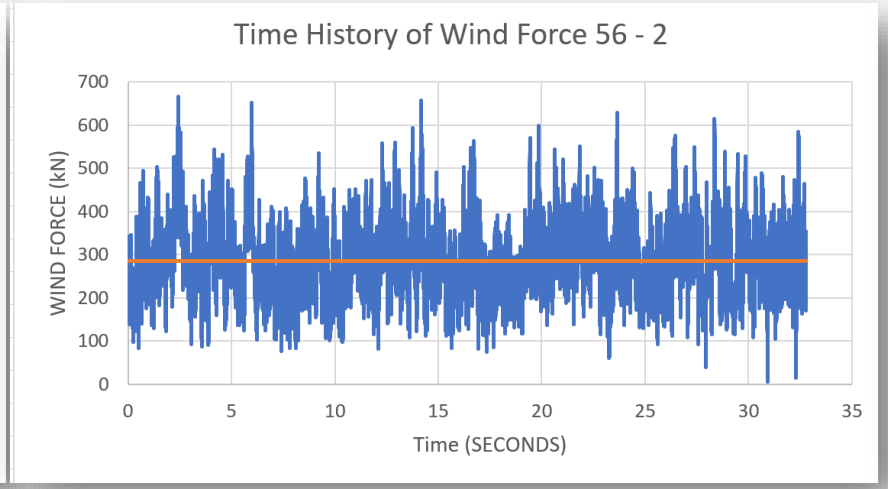
- The wind pressure varies
  - Along height
  - Various parts of the building at same height
  - With time
  - With Frequency
- This variation should be considered in analysis and design explicitly

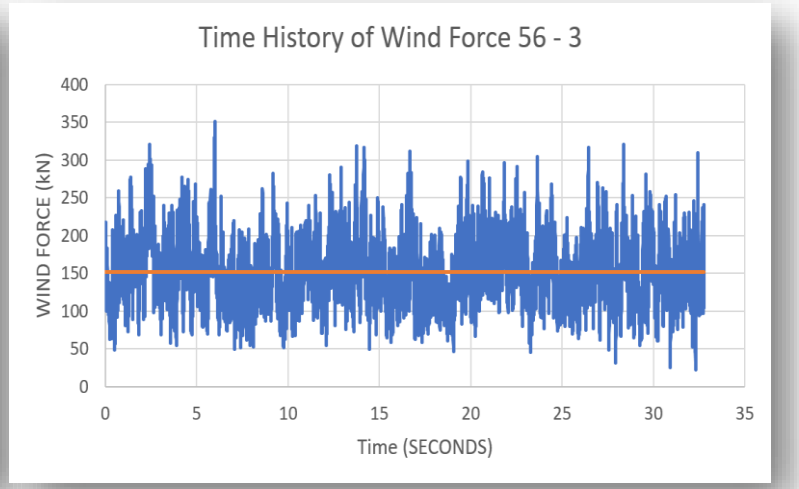


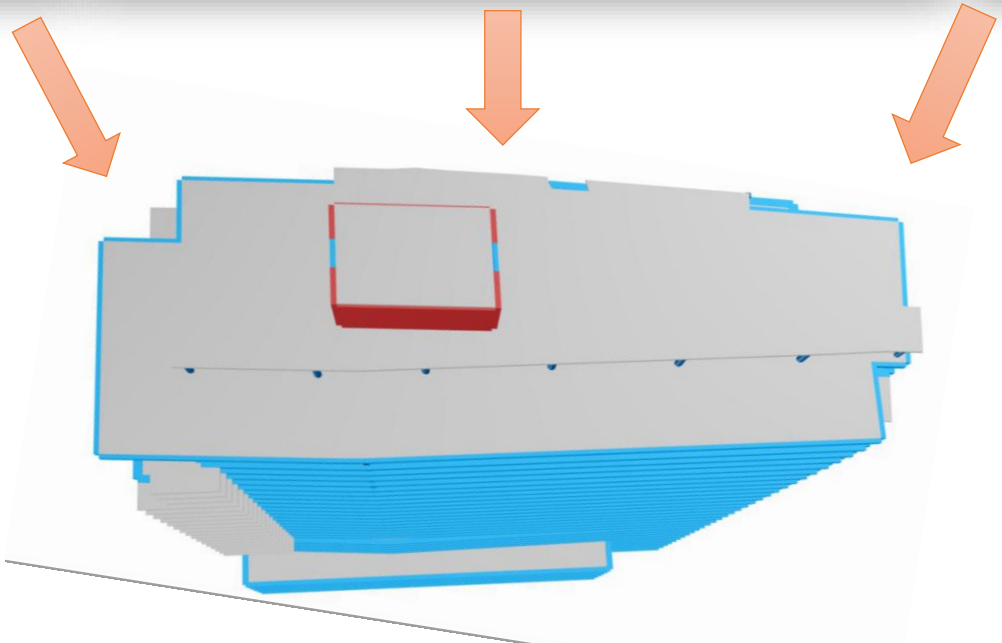


# Wind Pressure Variation and Dynamic effects



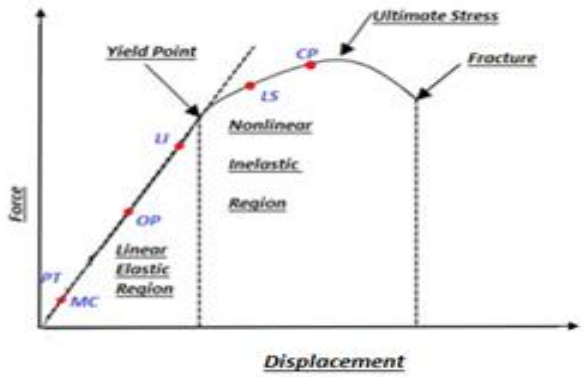



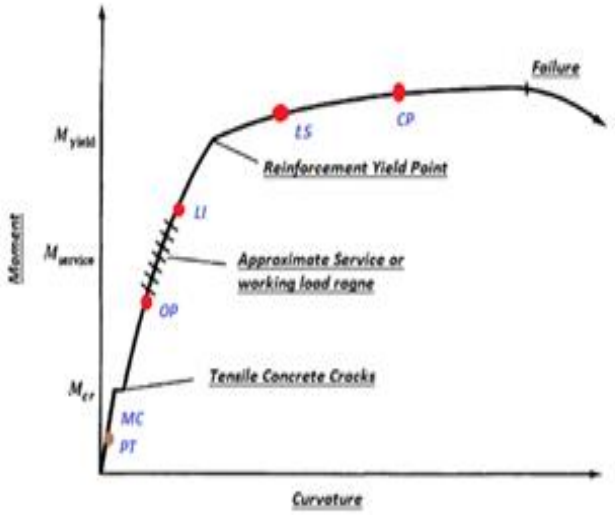



# Sample Structural Performance Criteria in Wind

| Return Period | Material Behavior |
|---|---|
| 1 | Uncracked |
| 10 | Uncracked |
| 50 | Cracked under Yield Point |
| 100 | Cracked under Yield Point |
| 475 | Cracked Beyond Yield Point |
| 1000 | Cracked Beyond Yield Point |




- "PT" Perception threshold
- "MC" Motion Comfort
- "OP" Operational
- "LI" Limited Interruption
- "LS" Life Safety
- "CP" Collapse Prevention

*(Based on various research papers)*

# Suggested Structural Performance Criteria for Wind

| Wind Return Period | Wind Performance Level | Structural System Response | Overall Damage | Wind Performance Objective | Design Criteria |
|---|---|---|---|---|---|
| **1 year** | Perception Threshold | No Permanent Interstory | Undamage | None Perception of movement | Bldg. Acceleration <5 milli -g |
| **10 years** | Motion Comfort | No Permanent Interstory | Undamage | Controlled Comfort | Bldg. Acceleration <15 milli -g |
| **50 years** | Operational | No Permanent Interstory | Undamage | Non-Structural Damage | Story drift is limited to 0.2% |
| **100 years** | Limited Interruption | No Permanent Interstory | Minor Damages | Structural Damage | Story drift is limited to 0.3% |
| **475 years** | Life Safety | Permanent Interstory | Major Damages | No Collapse | Story drift is limited to 0.5%<br>Residual Drift < h/600 |
| **1000 years** | Collapse Prevention | Permanent Interstory | Extensive Damages | No Collapse | Story drift is limited to 1%<br>Residual Drift < h/500 |

# Compare

# PBD Wind and PBD Earthquake

(Using ASCE 41 as a sample)

| | Wind | Earthquake |
|---|---|---|
| **Time Varying Loading** | Wind Tunnel Testing | Site Specific Investigation |
| **Loading** | Mean + Fluctuating + Resonant | Fluctuating + Resonant |
| **Overall Structural Damage** | ASCE 41-13 | ASCE 41-13 |
| **Structural System Response** | ASCE 41-13 | ASCE 41-13 |
| **Members Deformation Control Limits** | ASCE 41-13 | ASCE 41-13 |
| **Material Behavior** | Uncrack to Crack under yield to Crack beyond yield point | Crack under yield to Crack beyond yield point |
| **Structural members controlled** | Some members are Force and Deformation Controlled | Some Members are Force and Deformation Controlled |

# Suggested Methodology in PBD for Wind

## Loads

- Wind Speed based on Local codes
- 6 level of return period of wind based probable occurrences
- 36 different wind attack angles
- Mean time varying load for each floor level
- Background time varying load each floor level

## Structural Analysis

- Linear Model with wind force thru code based design
- Non-Linear Model reinforcement from linear model wind code based design
- Check Structure Global response from Wind Mean, Background and Resonant Force
- Apply Mean and background time varying force and Resonant Equivalent static Force

## Design/Post Processing

- Check and oversell response
- Member's strength capacity
- Member ductility as needed
- Deformation limits
- Motion limits

Can be obtain from wind tunnel consultant

# Running the Time History Analysis for Wind

| | |
|---|---|
| Time history functions | • 1 to 3 levels of wind intensity<br>• 3 components for 36 wind directions, at several story along height<br>• Total number of time history function will be **108 x levels x story** |
| Load patterns | • 3 components of point load coefficients<br>• Total number of load pattern will be **3 patterns** |
| Load cases | • 3 components of load being applied simultaneously for each wind direction<br>• Total number of load case will be **36 cases** |
| Load combinations | • Compliance with structural standard code |

# Related Development and Research

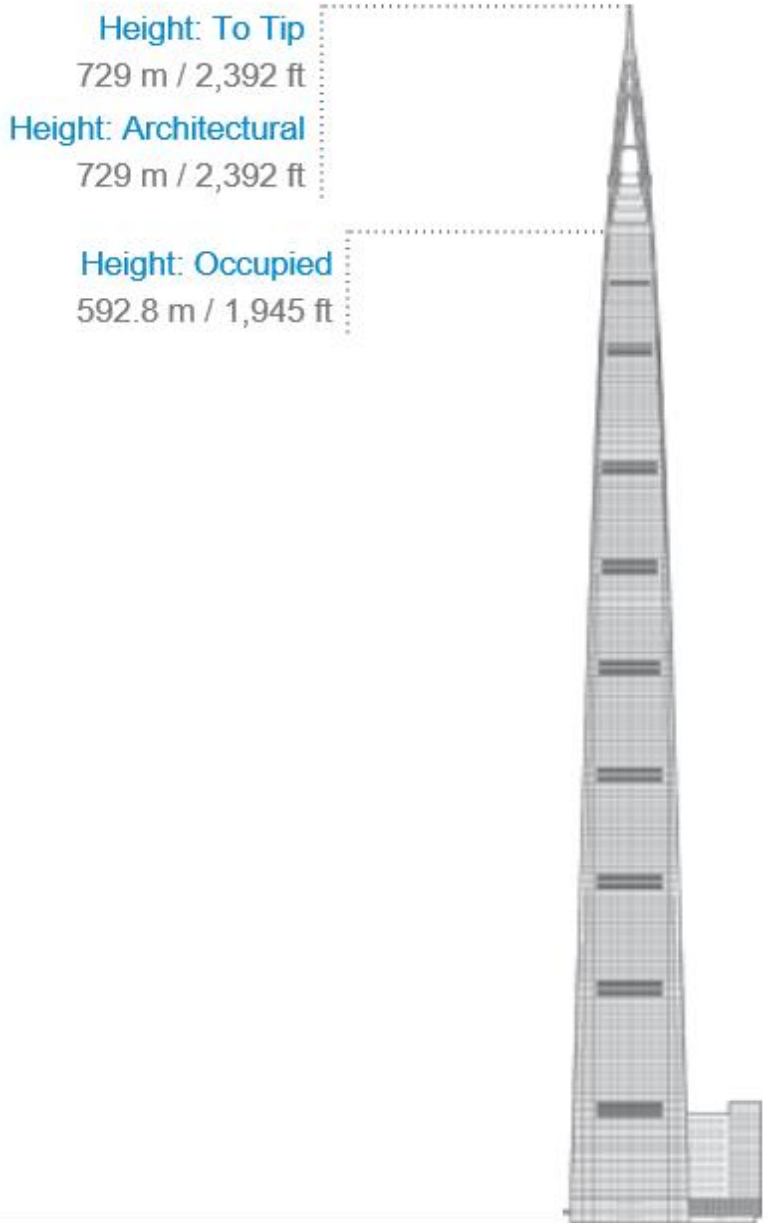
- *A Framework for Performance-based Wind Engineering*
  - Provides a comprehensive concept and process for Wind PBD
- *On the Design of High-Rise Buildings for Multihazard Fundamental Differences between Wind and Earthquake Demand*
  - A High rise tall building was subjected earthquake and wind forces comparison was conducted in terms of Story Displacement, Story drift and Acceleration of the buildings
- *Wind effects on High Rise Building*.
  - Shows Design Criteria needed to be check in High Rise Building subjected to wind force, Human Comfort Limit and The Rule of Thumb in natural frequency of a Building.
- *Wind loading in Tall Building*
  - Tells about what are the different types of wind designs, Design Criteria needed to be check in high rise building subjected to wind force.
- *Dynamic Effects A comparative Study of Provisions in codes and standards with Wind Tunnel data*
  - shows the different gust factor of different country wind codes and compare them with wind tunnel result

# High-Rise Buildings undergone PDB for wind

**Suzhou Zhongnan center, China**

Built in 2014
Design by Thornton Tomasetti

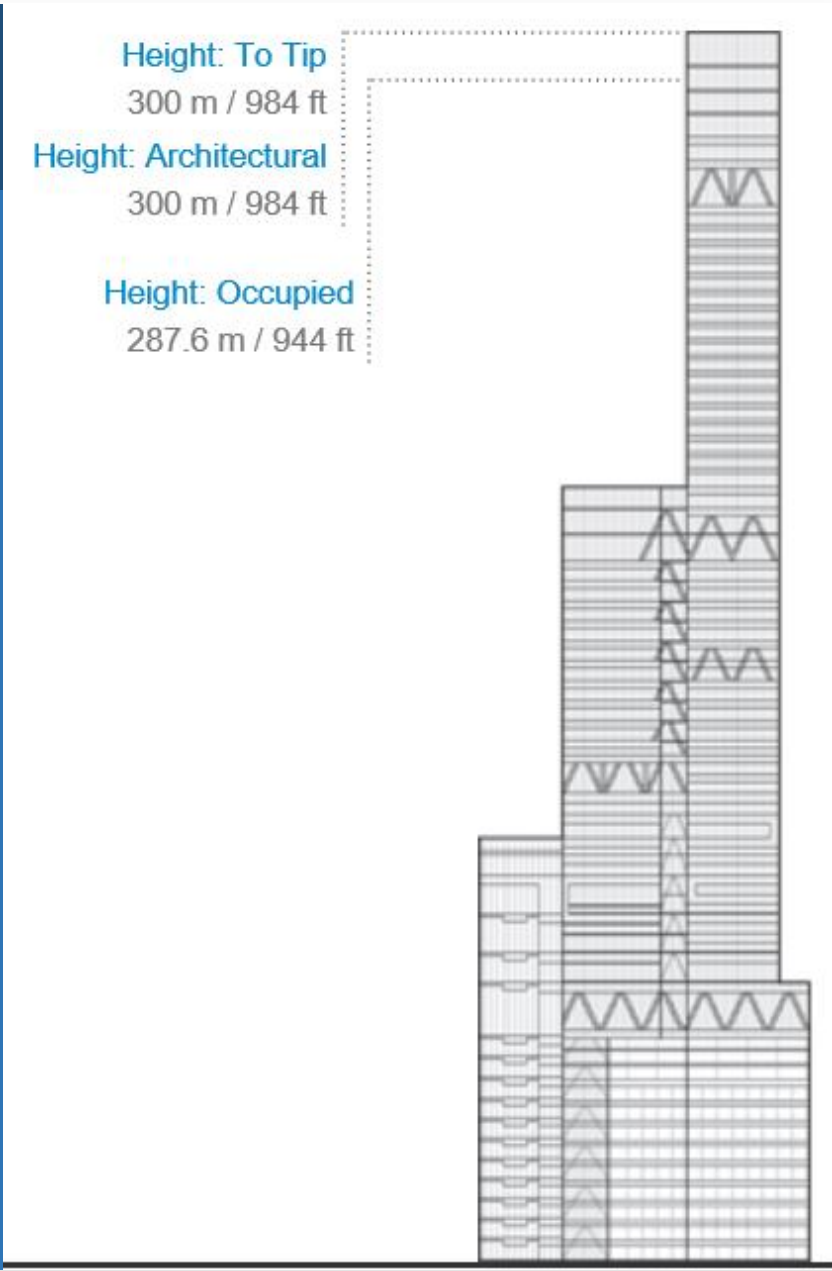
Satisfied different level of design criteria based the wind speed probable occurrences, comfort to strength criteria



# High-Rise Buildings undergone PDB for wind

## Abeno Harukas, Japan

- Built in 2014
- Design by Takenaka Corporation
- Satisfied different level of design criteria based the wind speed probable occurrences, comfort to strength criteria
- Uses various energy dissipating devices and out trigger belts in order control vibration from wind excitations



# What is being done at AIT

**Structural Lab**
Shake table, Cyclic Actuator, strong floor

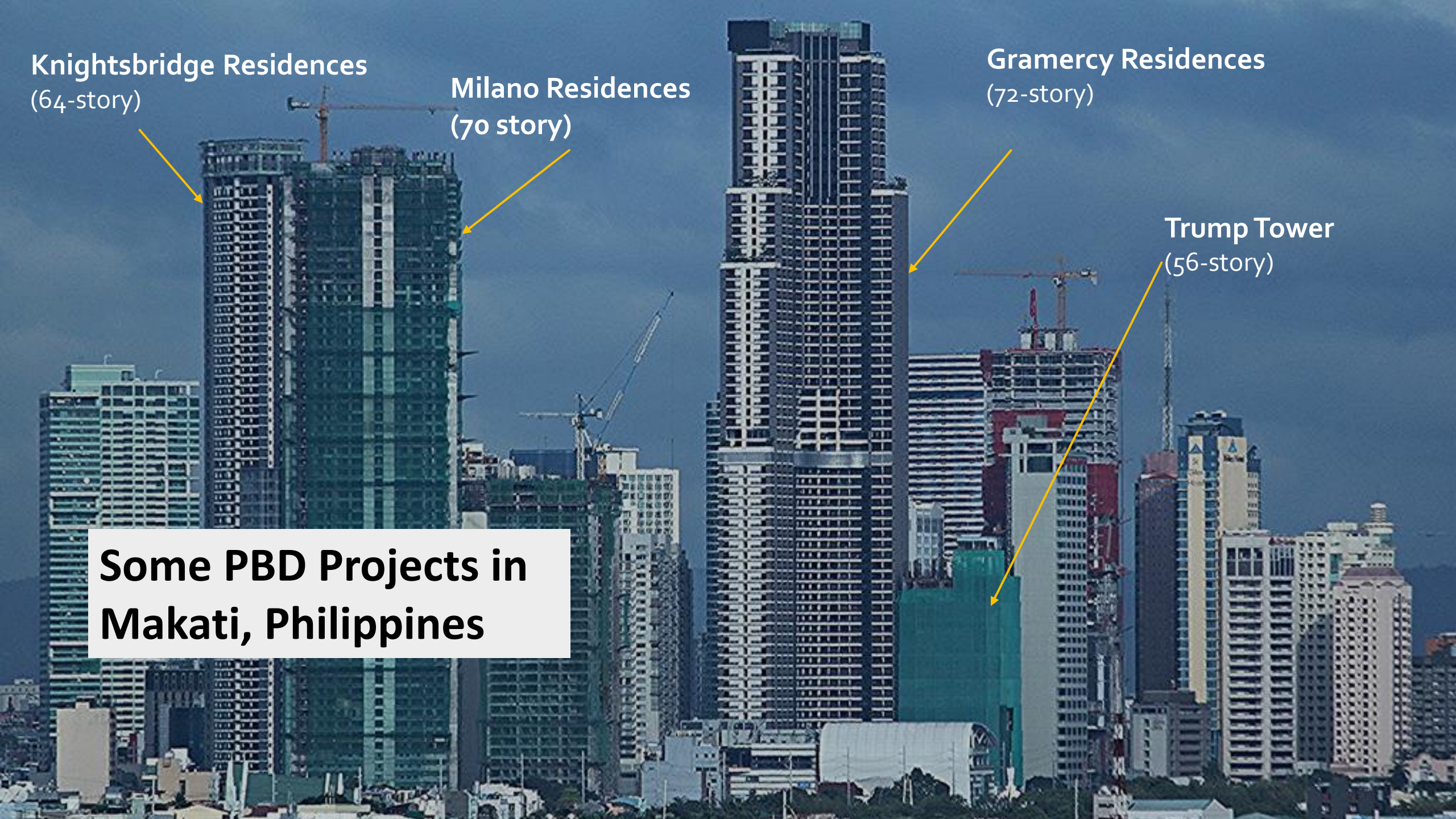
**Teaching, Research**
Tall Buildings, Wind and Earthquake Engineering

**Practical Experience**
of over 100 PBD Projects

**Development and application of Integrated PBD for Wind and Earthquake**

**CSi**
Software Developer

**Partners**
Structural Engineers




# Some PBD Projects in Makati, Philippines

# What is the outcome and impact

# Benefits

- More explicit way to define and measure performance for wind effects in tall buildings
- Obtain consistency between EQ and Wind design and reduce negative effects of wind design or EQ performance
- Economy and cost effective design for both wind and EQ
- Enhanced overall performance and reliability of buildings
- Advance the state of the art to integrated resilience based design

# Thank you

# References and further reading



**A Framework for Performance-based Wind Engineering**

Lawrence Griffis[1], Viral Patel[2], Susendar Muthukumar[3] and Sridhar Baldava[4]



**Engineering Objectives for Performance-Based Wind Design**

Russell Larsen[1]; Ron Klemencic[2]; John Hooper[3]; and Kevin Aswegan[4]

ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/272360283

Performance-based design optimization of tall concrete framed structures subject to wind excitations

**Article** *in* Journal of Wind Engineering and Industrial Aerodynamics · April 2015

DOI: 10.1016/j.jweia.2015.01.005

Hindawi Publishing Corporation
Shock and Vibration
Volume 2015, Article ID 148681, 22 pages
http://dx.doi.org/10.1155/2015/148681

Hindawi

*Research Article*

**On the Design of High-Rise Buildings for Multihazard: Fundamental Differences between Wind and Earthquake Demand**

**Aly Mousaad Aly and Srinivasa Abburu**

# References and further reading

**Wind effects on high rise buildings**

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P. Mendis, T. Ngo, N. Haritos, A. Hira
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B. Samali
*University of Technology Sydney, Australia*
J. Cheung
*Monash University, Australia*

**Serviceability Limit States Under Wind Load**

LAWRENCE G. GRIFFIS

FIRST QUARTER / 1993

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