The background of the entire page is an aerial photograph of a megacity, likely Hong Kong. A prominent, tall, blue-glass skyscraper stands out in the center. The surrounding area is densely packed with various other buildings, including residential blocks and commercial structures. In the background, a large body of water is visible, with many small boats and a bridge in the distance. The sky is clear and blue.

# Megacities Building Sway Considerations in Elevators Design for Mega Tall Buildings

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### ■ Work Experience

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# Understanding sway analysis





# Sway analysis



## Sway analysis

- The building sway analysis refers to an analysis on the building behavior in wind conditions **by the builder**.
- It covers many aspects which considerably affect the functionality of the elevator system in a building.
- It may be empirical (wind tunnel based) and theoretical (code based)

## Frequency/resonance analysis

- Due to the nature of elevator systems, the tension in the elevator ropes changes as a function of the car position in the elevator shaft. Therefore, after certain travel - depending on the properties of the building and elevator - areas where resonance exist cannot be avoided.
- Frequency/resonance analysis **by elevator provider** tries to determine the location and extension of the problem.



# Building Frequency

- Building frequency is not gained by wind tunnel testing but rather provided by the structural engineer, who has to make simplifications on the building design, which cause deviations in the building frequencies (typically 0...- 20 %).
- The building frequencies can also be estimated. One common approximation is  $46/H$  –approximation, where  $H$  is the building height.
- Based on actual measurements the frequencies gained by approximations are not less accurate and the predicted frequencies tend to be lower than the  $46/H$  –approximation. [1].
- In Japan a  $67/H$  –approximation has been adopted based on field measurements [2].
- Even if uncertainty exists the frequency analysis is an important part of the elevator design. It gives an overall understanding of the location and extent of the resonance areas.

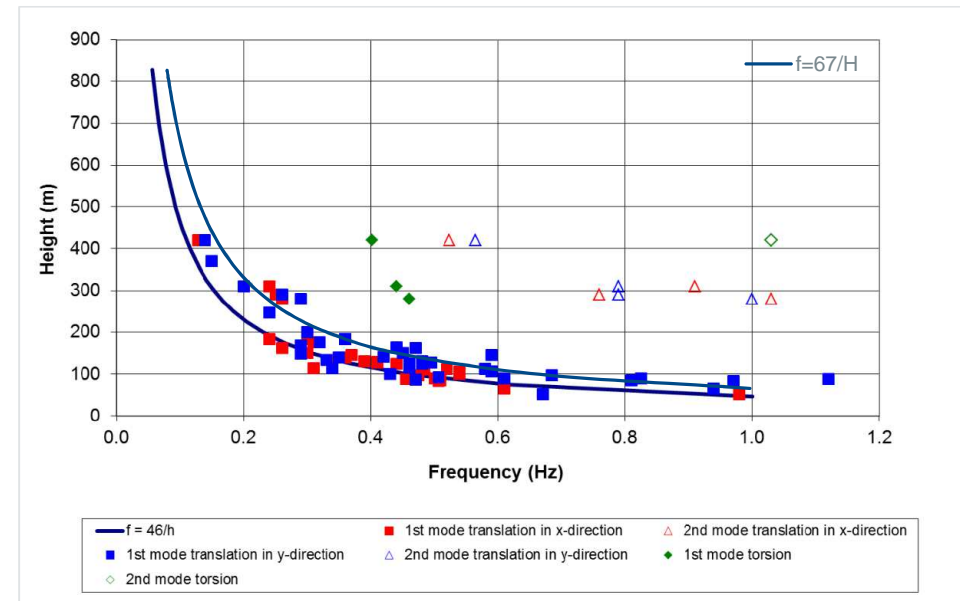


Figure 1. Measured building frequencies [1] superimposed with  $67/H$ -curve by author.

# Wind Response



- In the **along-wind** direction the building is not excited at a certain frequency. The amplitude can be significant, but the implications to the elevator systems are moderate due to lack of resonance.
- The **crosswind** response is often dominated by vortex shedding, which produces a constant excitation force at a certain frequency. If this frequency coincides closely with building natural frequency, the building starts to resonate. If resonance is also present at that point of time with the elevator system, energy accumulates quickly in the elevator ropes resulting in large rope sway amplitudes.
- In building design phase solutions can be found which reduce excitation caused by the vortex shedding and place it away from the building natural frequency at higher wind speeds. Methods include tapering the building, step-backs, changing corner shape and shape variation with height or changing the dynamic characteristics of the building (including mass, stiffness, mode shapes and damping [1,4].
- If not successful, the behavior of the whole building will be problematic.

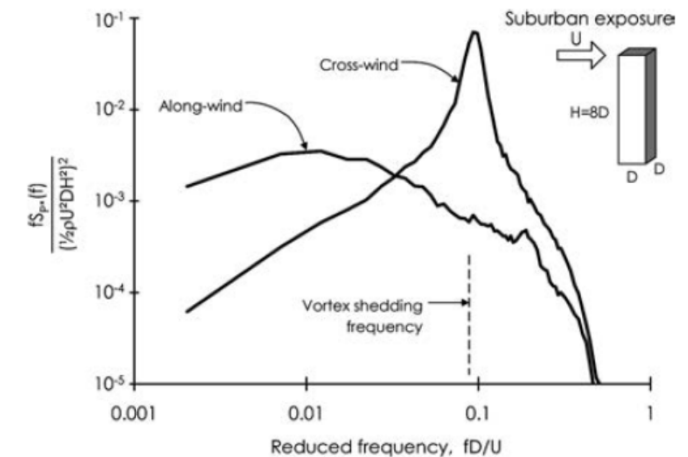


Figure 2. Aerodynamic load spectra [3].

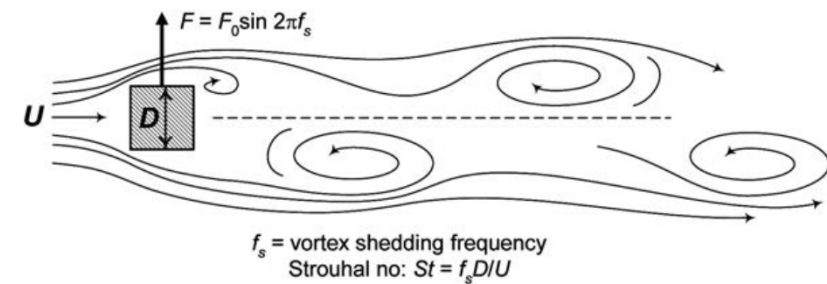


Figure 3. Vortex Shedding [3].

# Wind Climate Model



- Typical wind climate models are based primarily on information measured close to the ground level (ca. 10 m)
- Wind loading at higher altitudes is based on modelling rather than measured data. A typical boundary layer model assumes that wind speed increases as a function of altitude. This works if wind is constantly coming from the same direction but e.g. not with thunderstorm downbursts.
- Depending on the used model, the excitations and return periods for higher building movement level can be considerable different.
- Local authorities can also impose requirements, which may not be in line with best available wind data. This can lead to inaccurately estimated wind loads or creation of two parallel set of calculations; one for authorities and other based on best estimate.





Scale	[km]	Time (Life Span)				
Marcoscale Global	4000 - 40 000				Westerlies Trade winds Long waves	
Marcoscale Synoptic	1000 - 4000			Cyclones Hurricanes		
Mesoscale	1 - 1000		Sea/Mountain Breeze Tornados Thunderstorms			
Microscale	< 1	Wind gust Building corner eddies				
		Seconds to minutes	Minutes to hours	Days to weeks	Weeks to seasons	

Figure 4. Cascading Scales in Meteorology [5,6].

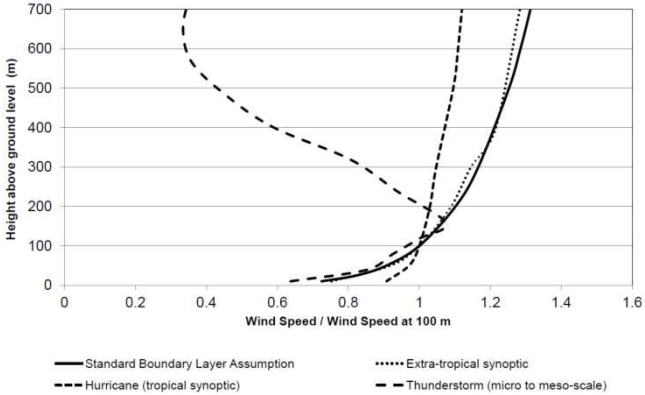


Figure 5. Wind Speed Profiles by Storm Type [5].

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# Human comfort criteria, building deflections and amplitudes



- The design of tall buildings is driven by the human comfort criteria in the top floors.
- Traditionally, the occupant comfort has been based on 5- and 10-year intervals
- Recent trend is towards one-year recurrence as it addresses better the discomfort of regularly occurring event. People tend to tolerate discomfort felt infrequently for short periods of time, but not as routine occurrences. [4].
- Several criteria for building motion exists (i.e. ISO6897-1984, ISO10137-2007, NBCC 1995, AS1170.2, CTBUH, etc.).
- These criteria differ in the evaluated recurrence period, vibration they assess (effective versus peak), if vibration frequency is considered and if the criteria is dependent on the occupancy (office, residential, hotel).
- For elevator engineering, the abundance of criteria makes it difficult to know what level of elevator service needs to be guaranteed at what conditions
- During extreme weather the elevators are expected to be parked and therefore the lower thresholds amplitudes have much more influence on the more common elevator design and operation (e.g. on yearly level).
- The accelerations for the comfort evaluation are either estimates based on aerodynamic databases (or building codes) or wind tunnel testing. The wind tunnel testing show better the effect of architecture of the surrounding building and the local wind climate, but contains still uncertainties in particular the wind climate model and structural properties of the building.
- During elevator design, the details how the building wind response was achieved is often not available.
- The elevator design has to be based on the excitation levels and return periods given in the wind analysis report even if it is known not to cover all aspects relevant to elevator design.
- The data obtained from the builder is an important parameter to help scale the severity of the sway problems.



# Annoyance factor

- The return period associated with strong winds and building movement does not give a comprehensive view of what is their effect on the elevator service.
- In a typical office building the active working hours can be expected to last approximately 10 h on 250 days per year, which represent roughly 30 % of the total. Outside this time frame, breaks in elevator service would cause less annoyance.
- Furthermore, of those working hours up-peak, lunch peak and down peak are most critical during which speed reduction of the elevator would be most inconvenient, but these represent only around 6% of total time. This means that the probability of speed reduction of short duration (typically < 15 min) associated in wind conditions like thunderstorms (refer to Figure 6) have low probability of generating substantial annoyance.
- In residential buildings, hotels, hospitals and other buildings expecting 24h service in climate conditions where gale winds of longer duration are dominant (see Figure 7), similar return period could be perceived much more annoying.

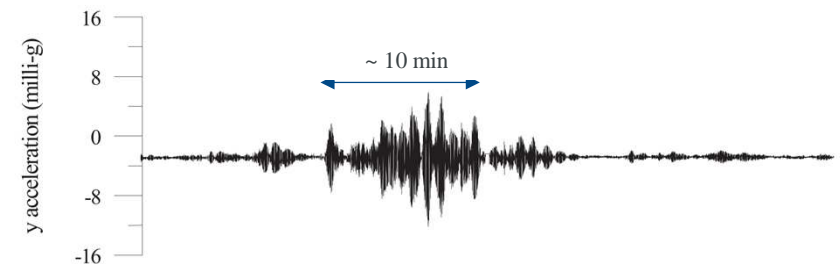


Figure 6. Time history of acceleration during thunderstorm [7].

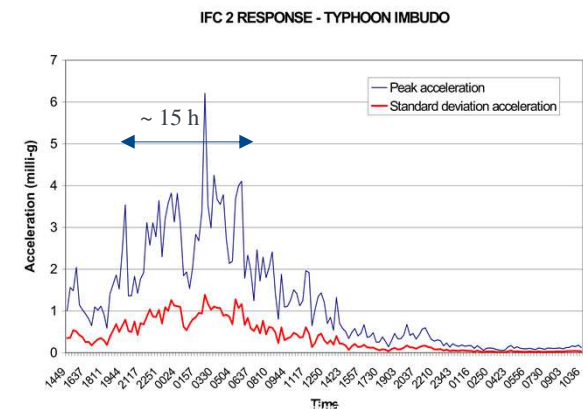


Figure 7. Building response during typhoon [8]

Resonance calculation





# Resonance Calculation



- Various papers focusing on elevator rope-sway simulations/studies have been presented in scientific publications, which can be classified in three main approaches:
  - Analytical Method
  - Finite Element Method (FEM)
  - Finite Difference (FD) method
- FEM is widely used in the studies of vibrating structures and can be considered as norm in structural engineering, but it often leads to heavy simulations.
- In FD-based methods the derivatives of the governing rope-sway equations are directly approximated and simple time-marching techniques can be used.
- The three different approaches are briefly described and a comparison of results of the models is presented.

# Sway Models



## Analytical model

- The model was presented in an article in Elevator World magazine [8]. Modal superposition approach and Lagrange energy-method are used to derive the dynamic equation for vibrating ropes and the arisen equation is solved analytically.
- One of the critical simplifications is that the tension is assumed to be constant in rope (value is the tension at rope half length).
- Results provided by this model are considered inaccurate. This is clearly demonstrated by comparison with other models.
- It would be possible to improve the accuracy of the predicted resonances of this model by modifying the rope tension, when the natural frequencies of the rope are computed.
- A significant drawback of this model is that the vibrating rope shape and the maximum amplitude are frozen in time, so travelling waves or sway build-up cannot be analyzed with this method.

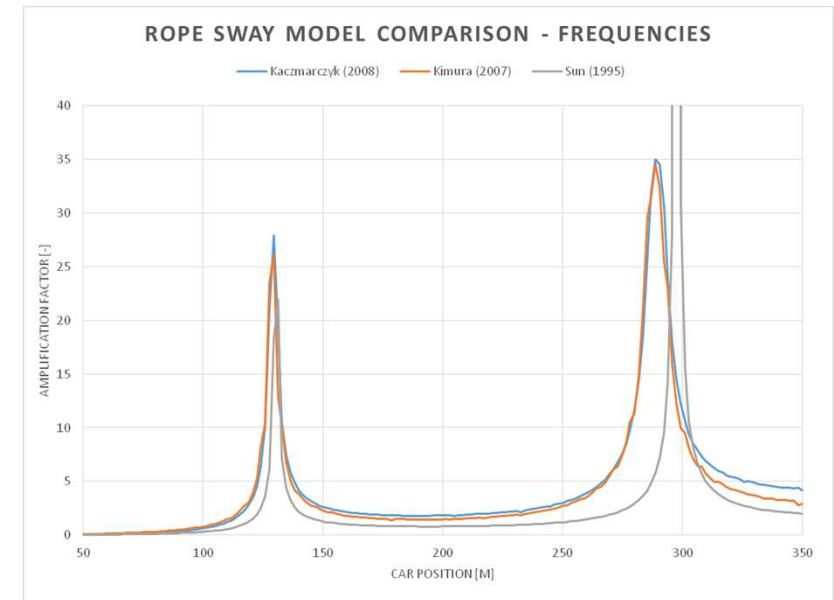


Figure 8. An example of results provided by these tools, with input parameters:

Travel = 350 [m]

Sway frequency of building = 0.200 [Hz]

Compensation rope weight per unit length = 2.06 [kg/m]

Number of compensation ropes = 4

Compensation rope tension weight mass = 3500 [kg]



# Sway Models



## FEM based model

- The model is described in detail in a paper by Stefan Kaczmarczyk [10]. This model is restricted to case, where only the upper end the rope is laterally excited, i.e. typical situation for compensation ropes.
- For stationary car simulations, the results from FEM and FD based models are found practically identical.

## Finite-Difference model

- This model has been presented in the Japanese Journal of Environment and Engineering [11].
- The model is based on second-order damped wave-equation.
- A clear benefit of this approach is that the effect of ropes hitting obstacles or dampers can easily be simulated. The computation is also relative fast for simple analysis.
- The drawbacks of this approach are related to numerical-aspects that may cause instabilities or oscillations.
- The benefit of the model is that it can simulate suspension ropes and compensation ropes for stationary and moving car.
- Additional benefit is that calculation routines that take into account e.g. the added tension in rope due to displacement can also implemented to this model.

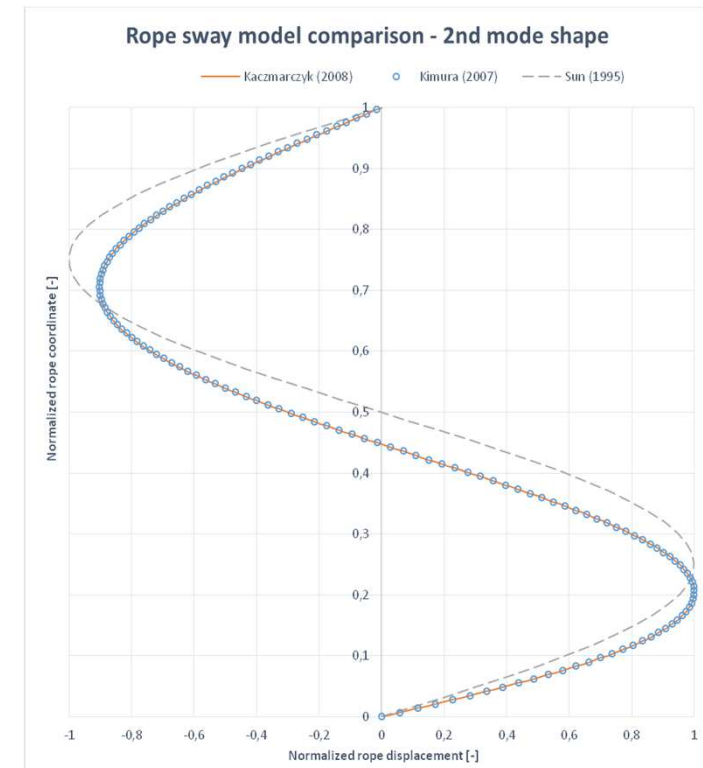


Figure 8. Sway model comparison, 2<sup>nd</sup> mode shape





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