

Chapter 2

LITERATURE REVIEW

2.1 General

This chapter provides a comprehensive literature review aimed at addressing research gaps and developing a theoretical framework and methodology for the present research study. The primary focus of the study is on the effects of across wind loading on tall buildings, and thus, the literature directly relevant to this area is extensively discussed. The chapter is structured into three main sections: along wind load, across wind loading on buildings, and torsional wind loading.

The first section examines the literature pertaining to along wind load. This entails a detailed analysis of relevant studies that have investigated the forces and pressures exerted by wind acting parallel to the main axis of structures. Following the discussion on along wind load, the second section delves into the literature related to across wind loading on buildings. This section specifically highlights the importance of considering wind forces acting perpendicular to the main axis of tall buildings. It explores the aerodynamic phenomena and complex interactions between wind and structures, such as vortex shedding, wake interference, and turbulence. By reviewing the existing research, this section aims to emphasize the importance of across wind loading on tall buildings. The third section focuses on the literature concerning torsional wind loading. It examines studies that investigate the wind-induced moments causing twisting of structures around their vertical axis. The section explores the challenges associated with torsional effects, particularly in buildings with irregular shapes, and emphasizes the need for proper analysis and design considerations to ensure structural integrity.

Through an extensive literature survey, this chapter identifies the research gaps that exist within the field. By critically analysing the existing literature, the chapter highlights areas where further research is needed to advance understanding and develop effective methodologies for assessing and mitigating wind-induced effects on tall buildings. Finally, based on the research gaps identified, the chapter establishes the objectives of the present study, setting the stage for the subsequent chapters of this thesis.

2.2 Along wind load

Along wind loading refers to the force or response induced by wind that aligns parallel to the wind direction. This influential phenomenon plays a pivotal role in the design considerations of tall buildings and structures. The formulation and advancement of along wind loading theory and methodologies can be traced back to the early 20th century, during which esteemed researchers such as Prandtl, von Karman, Davenport, and numerous others made noteworthy contributions towards comprehending the impact of wind on structures.

One of the pioneers in the study of wind effects on structures was Ludwig Prandtl, a German physicist and engineer. Prandtl's groundbreaking work (Prandtl. 1904) in fluid mechanics laid the foundation for understanding the behaviour of wind flow around buildings and structures. His theories and experiments formed the basis for later research on wind-induced forces. Another influential figure in along wind loading was Theodore von Kármán, a Hungarian-American engineer and applied mathematician. Von Kármán's work on aerodynamics and turbulence (Von Kármán 1949) provided valuable insights into the behaviour of wind flows. His research contributed to the understanding of the wind-induced vibrations and responses of structures. In the mid-20th century, Alan G. Davenport, a Canadian engineer, made significant contributions to the study of wind effects on structures (Davenport 1961,1965). Professor Davenport's approach to wind

loading involved integrating the essential components into a thought chain, analogous to a physical chain where the strength relies on its weakest link. Figure 2.1 depicts the association of his ideas in the form of a chain. As a result of his numerous accomplishments and contributions, the International Association of Wind Engineering has officially recognized and named his approach to wind loading as the “Alan G. Davenport Wind Loading Chain”. This acknowledgment acknowledges Professor Davenport's significant achievements and underscores the importance of his work in the field of wind engineering. Isyumov (2012) provided an in-depth examination of the invaluable contributions by the Alan G. Davenport to the field of wind engineering.



Figure 2.1 Wind loading chain proposed by A.G. Davenport

Davenport (1967) proposed the “Gust loading factor” (GLF) approach to evaluate the along wind forces on structures. The majority of global codes and standards rely on the "gust loading factor" methodology to evaluate the dynamic effects of along-wind loads on tall structures. After the Davenport several authors modified the GLF approach [Vellozzi and Cohen (1968), Vickery (1970), Simiu and Scanlan (1996), and Solari (1993a, b)]. Major international codes and standards have embraced these modified versions of the GLF approach. Kijewski and Kareem (1998) and Zhou *et al.* (2002) compared major international wind codes [AIJ 1996, NBCC 1995, BS 1995, EN 1995 and China standard (1987), ASCE 7-95] in the perspective of along wind loading.

2.3 Across wind load

The prediction of dynamic along-wind response in structures has shown reasonable accuracy through the utilization of the gust factor approach. However, when it comes to

cross-wind excitation mechanisms, the complexity increases significantly. Unlike along-wind forces, the understanding and prediction of forces acting perpendicular to the wind direction have posed greater challenges due to their intricate nature. Across wind vibration in tall buildings is influenced by three main mechanisms. Firstly, vortex shedding occurs when flow periodically separates from the building's surface, creating an oscillating force. The shedding of vortices exhibits a dominant periodicity, which is characterized by the appropriate Strouhal number specific to the building's shape. Large amplitude vibrations arise when the shedding frequency matches the structure's natural frequency. Secondly, the incident turbulence mechanism occurs due to changes in wind speed and direction, inducing varying lift forces on the building. Sections with high lift or pitching moment slopes generate crosswind forces based on wind speed and angle of attack. Lastly, higher derivatives of crosswind displacement, such as galloping, flutter, and lock-in, are influenced by turbulent effects and affect the aerodynamic derivatives of the structure. [Mendis *et al.* (2007), Hou and Jafari (2020)]

A few initial studies were conducted by Saunders (1974), Melbourne (1977) and Kwok (1977) to understand this phenomenon. To estimate the forcing function, several experimental techniques have been developed by Saunders and Melbourne (1975), Kareem (1979) and Rheinhold and Sparks (1979), enabling the computation of the building's cross-wind response. These techniques aim to provide valuable insights into the dynamics of the building under cross-wind conditions. Kareem (1992) have provided valuable testing results of the across wind loads of tall buildings with typical cross sections. Multiple international codes and standards offer detailed guidelines for assessing the impact of across-wind loading on tall buildings, such as IS: 875 (Part 3)-2015, AIJ 2004, and NBC 2005. Liang *et al.* (2002) conducted an investigation into various factors affecting across-wind loads on tall buildings. Zhang *et al.* (2017)

conducted wind tunnel tests using a series of aeroelastic models with different cross-sections to analyse the dynamic responses to across-wind forces. Kwok (1982) applied the wind pressure integration technique to improve the accuracy of estimating across-wind aerodynamic forces on tall buildings and also provided a design procedure to estimate the across wind deflections and acceleration response. Cheng *et al.* (2001) and Marukawa *et al.* (1992) performed experimental studies on across-wind aerodynamic forces for tall buildings and derived empirical relationships for the corresponding power spectral density (PSD). Venanzi and Materazzi (2012) developed a semi-analytical method for predicting the across-wind aeroelastic response of square tall buildings. Numerous studies have reported that super high-rise buildings generally experience larger dynamic responses in the across-wind direction compared to the along-wind direction. The importance of across wind load is discussed in the Introduction chapter. To summarize, the available literature emphasizes the significance of considering across-wind loading on tall buildings, with various researchers providing insights into the factors influencing these loads and proposing methods to accurately predict the dynamic responses in the across-wind direction.

2.3.1 Mitigation of across wind load

There are two primary methods for mitigating across wind loads on a tall building. The first approach involves altering the mechanical properties of the building, such as its damping, mass, and stiffness. The second approach entails modifying the building's geometry, specifically by making adjustments to the corners and along its elevation. By employing these methods, the adverse effects of across wind loads can be effectively addressed and reduced. According to Zhaoa *et al.* (2011) Stiffness plays a critical role in ensuring structural stability and response, making it a significant aspect to consider. When faced with high wind speeds and low stiffness, structures become more vulnerable to

vortex-induced vibrations in the crosswind direction. Enhancing the stiffness and mass of a structure helps reduce the magnitude of vibrations. However, in many situations, increasing the mass and stiffness is undesirable due to the associated costs and the potential for increased seismic forces in certain cases. The ability of a structure to dissipate energy is referred to as damping. A common approach nowadays is to increase the damping of the structure by incorporating auxiliary damping devices. This practice has gained popularity in recent times [Kareem (1983), Kareem and Kijewski (1999) and Irwin and Breukelman (2001)].

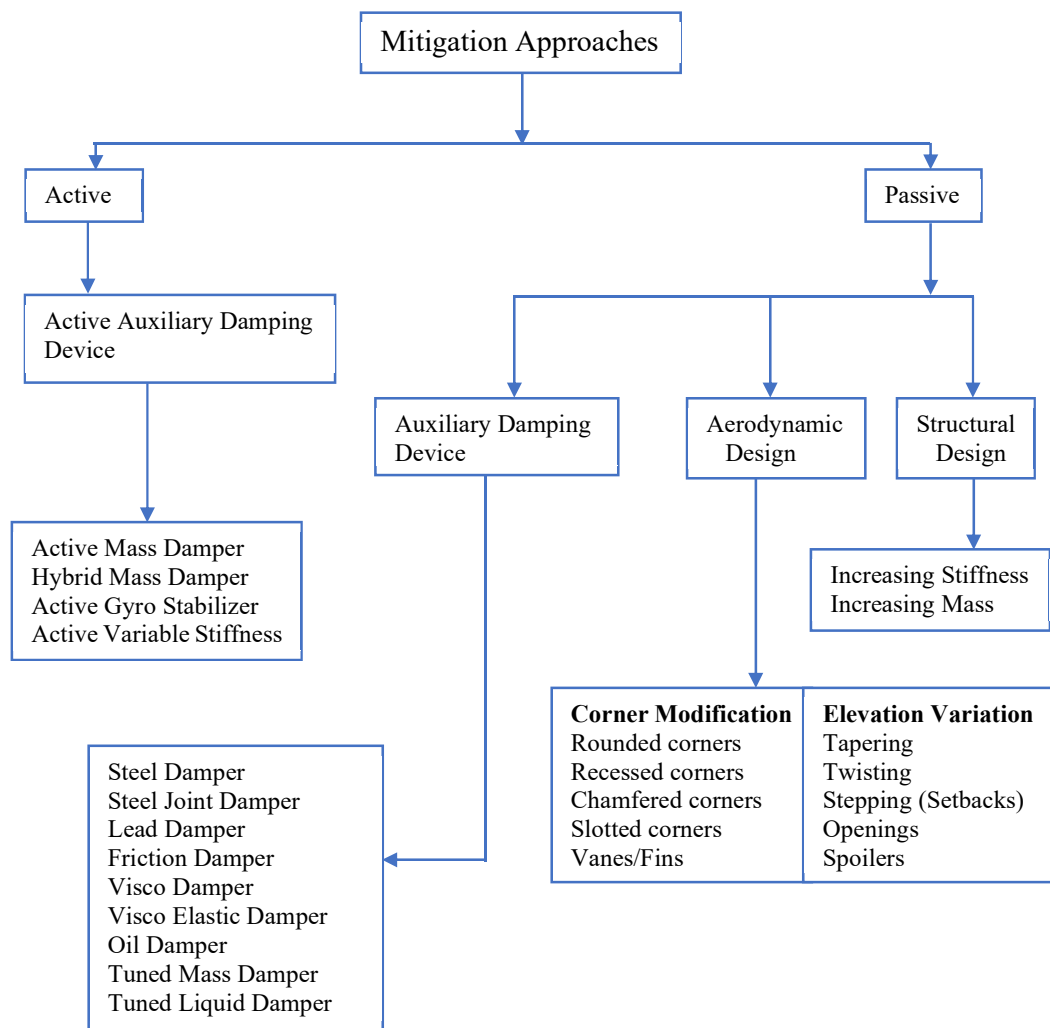


Figure 2.2 Various types of mitigation approaches

Enhancing the aerodynamic performance of tall buildings against wind forces can be achieved through various strategies, as shown in Figure 2.2. Rounded corners, as proposed by Kareem *et al.* (1999), Kawai (1998), and Kwok (1995), present an effective method. Tapering, as demonstrated by Kim and You (2002) and Kim *et al.* (2008), exhibits a more pronounced impact in the direction across the wind than along it. Adapting the cross-section shape concerning the building's height, as suggested by Irwin *et al.* (2008), proves particularly effective in mitigating forces acting across the wind. Research by Dutton and Isyumov (1990), Isyumov *et al.* (1992), Miyashita *et al.* (1993), and Okada and Kong (1999) underscores that openings in the upper half of buildings, especially along the wind direction, can substantially reduce responses to forces across the wind. However, the success of this approach is contingent upon the specific location and size of these openings. Moreover, Dutton and Isyumov (1990) note that the effectiveness of such gaps may be influenced by the turbulence level in the approaching flow. Twisted building forms emerge as a viable option for reducing vibrations induced by vortices, as noted in limited studies like Kelly *et al.* (2012).

2.4 Torsional wind load

Accurately estimating torsional wind load remains a challenging task in the field of wind engineering. One of the key factors influencing torsional loading is the shape of the building's cross-section. Extensive research has shown that triangular-shaped buildings exhibit a significantly stronger dynamic torsional response compared to other shapes, as highlighted by Cheung *et al.* (1992) and Beneke and Kwok (1993). Among quadrilateral shapes, parallelograms experience unusually high torsion, with a 33% increase in comparison to rectangular shapes, according to Boggs *et al.* (2000). Square buildings, as noted by Hui *et al.* (2017), have significantly higher mean and fluctuating torsion

coefficients, about 1.5 times greater than rectangular buildings. The wind response of tall buildings has been extensively studied, in the work of Hou and Jafari (2020).

Early progress in understanding torsional wind load was made through wind tunnel studies conducted by Patrickson and Friedmann (1976), Foutch and Safak (1979), and Surry and Lythe (1981). Notably, Kim *et al.* (2014) found that supertall buildings experience minimal torsional moments based on their wind tunnel tests. Torsional wind loads have been found to be correlated with wind loads in both along-wind and across-wind directions, as highlighted by Zou *et al.* (2016). In a study conducted by Tamura *et al.* (2018), different buildings with polygonal cross-sections were examined to understand their torsional behaviour. The researchers found that the number of sides in the polygon has an impact on the torsional moment coefficients. Interestingly, as the number of sides increases, there is a decrease in the torsional moment experienced by the buildings. In simpler terms, buildings with more sides tend to experience less torsional force compared to those with fewer sides. Zou *et al.* (2020) identified the advantage of aligning the building face with the longer side perpendicular to the dominant wind. They also observed that windward eccentricity enhances torsional dynamic performance, while leeward eccentricity has the opposite effect.

Approximately three decades ago, Xu *et al.* (1992) conducted a study demonstrating the successful reduction of torsional vibrations in buildings through the appropriate selection of tuned mass dampers (TMDs). In a comprehensive review, Kareem *et al.* (1999) also highlighted the effectiveness of dampers in mitigating torsional vibrations. Tse *et al.* (2012) evaluated the performance and cost efficiency of a smart tuned mass damper system in suppressing wind-induced lateral-torsional movement in tall structures. Through their research, Ross *et al.* (2015) showcased that tuned liquid damper (TLD) systems significantly reduce the twisting motions of high-rise buildings. Pozos-Estrada

and Hong (2015) concluded that TMDs with both linear and nonlinear damping mechanisms, along with considering the influence of correlated wind load effects, are instrumental in reducing peak response caused by wind-induced torsional load. Furthermore, they emphasized the importance of selecting appropriate dampers. Akyürek *et al.* (2019) proposed a novel integrated control system (ICS) approach designed to enhance the safety and performance of torsional irregular buildings. Their findings suggest that the ICS approach is more robust than TMDs in minimizing inter-story drift. Collectively, these studies provide substantial evidence supporting the efficacy of TMDs in mitigating torsional wind response.

2.5 Literature gap

Based on an extensive literature review, it is evident that numerous researchers have examined the impact of geometric alterations, such as corner modifications (Kareem *et al.* (1999), Kawai (1998), and Kwok (1995)) and variations in building shape along the height (Kim and You (2002) and Kim *et al.* (2008)), as well as the influence of damping (Kareem (1983), Kareem and Kijewski (1999) and Irwin and Breukelman (2001)) on across wind loads. However, there remains a considerable gap in the existing body of research regarding the comprehensive understanding of the interplay between structural, geometrical, and wind field parameters in relation to the across wind load experienced by super high-rise buildings. The limited availability of studies addressing this specific aspect highlights the need for further investigation and analysis to establish a robust understanding of the role played by these parameters in shaping the across wind load characteristics of super high-rise structures.

Following an extensive literature review, it becomes evident that numerous studies have delved into the topic of corner modifications for square or rectangular-shaped buildings. However, these studies have predominantly focused on a fixed 10% corner

modification (Irwin (2008), Kareem *et al.* (1999), Kawai (1998), and Kwok (1995)). This observation has sparked the author's curiosity to explore the impact of different percentages of corner modification across various techniques, including chamfering, rounding, recessing, and double recessing. This gap in the existing literature serves as a prime motivation for the author to conduct a comprehensive investigation in this area.

Additionally, shear lag, which diminishes the efficiency of tube-type structures [Khan and Amin (1972) and Coull and Bose (1975)]. Considering shear lag, Mahjoub *et al.* (2011) evaluated the performance of the framed tube by assessing the axial stress distribution on the exterior panels. Leonard (2007) examined the shear lag effect in diagrid systems with a given factor. Moghadasi *et al.* (2020) examined the relationship between shear lag and lateral loads (wind and earthquake) on concrete tubular structures. The effect of terrain category, aspect ratio, and number of storeys on the shear lag phenomenon in RCC-framed tube structures was examined by Kumari *et al.* (2022). To the best of the author's knowledge, the investigation into the effects of torsional wind loading on framed-tube buildings has not been undertaken in previous research. Therefore, this thesis work represents an important step toward filling this research gap and contributing to our understanding of wind loading dynamics in high-rise structures.

2.6 Objectives

In light of the literature review and identified research gaps, the thesis establishes the following objectives:

- To analyse the effect of plan aspect ratios on along wind and across wind loads on super high-rise buildings.
- To evaluate the effect of height aspect ratios on along wind and across wind loads on super high-rise buildings.

- To investigate the effect of wind parameters on across wind load of super high-rise buildings.
- To examine the effect of structural parameters on across wind load of super high-rise buildings.
- To ascertain the effect of corner modifications on a square cross-section building under wind load.
- To see the effect of torsional wind load on framed-tube buildings by observing the axial force of the columns.