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Methodologies to mitigate wind-induced vibration of tall buildings: A state-of-the-art review

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ABSTRACT

This paper reviews the state-of-the-art and –practice on various methodologies developed to control the wind-induced vibration of tall buildings. Tall buildings experience wind-induced vibration in the along- and across-wind directions depending on the wind direction, building shape, height, and structural properties. It is possible to control the wind response of buildings through passive, active, and semi-active systems. Damping systems, which are widely used to reduce the structural vibrations, are reviewed, and their performance in alleviating the building vibration is discussed. It was found that the application of conventional dampers needs to be reassessed to ensure their efficiency in dissipating the energy, especially caused by wind loads. Specific attention has been given to the aerodynamic modification of building shapes considering their effectiveness and high popularity within the wind engineering community. A comprehensive review of the existing wind tunnel experiment and Computational Fluid Dynamics (CFD) studies are conducted here to present the past and recent achievements on the response mitigation of tall buildings. A comparative study on the performance of different systems has been provided that can provide a commencing point for future studies. The existing challenges and their solutions are explained, and suggestions for future studies are proposed. It is expected that the information provided in this paper will facilitate further research in the area of wind-induced vibration mitigation approaches of tall buildings.

1. Introduction

High demand for residential and business spaces and advancements in construction techniques have resulted in the massive construction of tall/high-rise buildings all around the world. According to the Council of Tall Buildings and Urban Habitat (CTBUH), there the number of tall buildings has an increasing trend with a projected addition of 175 tall buildings in 2020 [1], as shown in Fig. 1.

As buildings become taller and with advances in construction techniques resulting in lighter and more flexible buildings, they become more susceptible to large-amplitude vibration. The slenderness for a tall building is defined by the ratio of the building's height to the smallest plan dimension. It was found that the large-amplitude vibration can easily occur for tall buildings whose slenderness is greater than five or those that have a fundamental frequency of less than 0.2 Hz [2]. Additionally, the mass adoption of lightweight and low-damping materials has made tall buildings more vulnerable to the lateral wind loads [3]. Large-amplitude vibration could lead to structural damage or even a catastrophic failure [4]. Occupant comfort is another concern caused by wind-induced vibrations. Occupant perception depends on the magnitude of the horizontal acceleration. There are several standards to determine the acceptable vibration of a tall building exposed to wind loads. The acceptable frequency for building vibration ranges from 0.1 to 1.0 Hz [9]; besides, other factors such as root mean square (RMS) or peak response values of the building vibration, recurrence interval, and the building type define the acceptable frequency. Fig. 2 shows the classification of occupants' perception of the wind-induced vibration in tall buildings. Given that wind-induced vibration plays an important role in the structural safety and occupant comfort, it is essential to develop measures that can reduce the vibration of tall buildings under wind excitations.

Tall buildings are prone to wind-induced cross dynamic response (due to vortex-induced vibration) and along-wind dynamic response (from turbulence-induced buffeting and torsional vibrations rooted in asymmetric loading) [6]. It is generally the cross-wind response that usually governs the strength and serviceability design criteria. Along-wind vibration originates from the buffeting load that is parallel to the wind direction. Torsional vibration is caused by the twisting torque along the building's vertical axis, which originates from the non-uniform wind load distribution [7].

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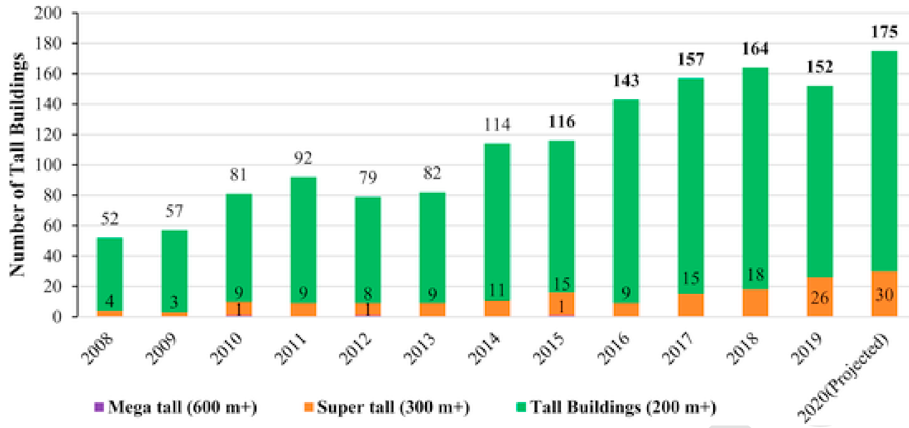

Fig. 1. Number of tall buildings completed by year [1].

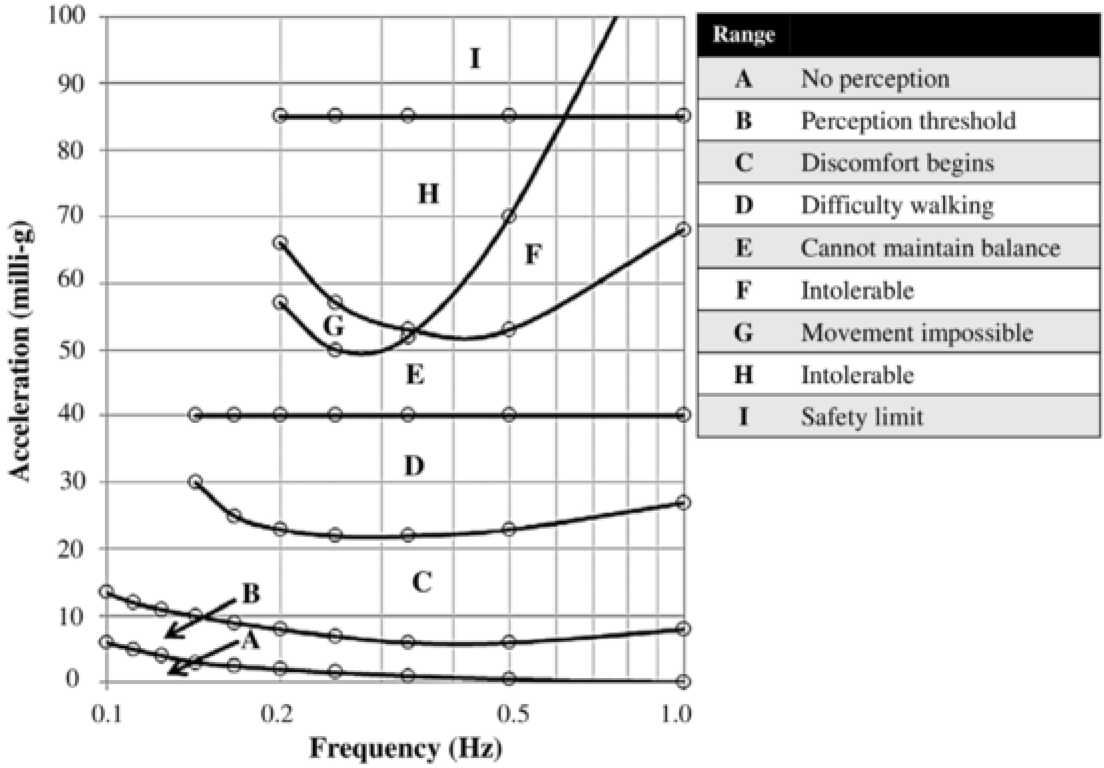

Fig. 2. Vibration limits and habitability reproduced from Ref. [5].

Traditionally, three different approaches have been used to suppress the wind-induced vibration: modifying the structural design, using either passive or active auxiliary dampers, and aerodynamic modification. Modifying the structural design results in reducing the wind-induced vibration by changing the structural properties such as mass and stiffness. However, the method is not economical as it will result in increasing the cross section of the framing system and subsequent construction cost. As such, this state-of-the-art review will specifically focus on the two latter approaches: auxiliary dampers (also called control systems) and aerodynamic modification.

The active control system can mitigate the wind-induced vibration of tall buildings by adjusting the structural damping or stiffness with a hydraulic or electro-mechanical actuator system. This system is also able to reduce the vibration over a wide range of frequency under varying excitation conditions. Moreover, the controller force can be executed in a controlled manner within a short period of time [8,9]. The downside to them, however, is the large consumption of energy to control the actuators and possibility of destabilization if the parameters are changed abruptly [10]. A passive control system refers to those that do not require installing the sensors or actuators with the external power supply to dissipate the vibrations. Damping devices have been widely used to control the vibration caused by wind load or earthquake for different types of structures such as cables [11], traffic signal lights [12], and buildings. Among various types of dampers, tuned mass dampers (TMDs) are the most popular ones that are implemented on tall buildings to dissipate the vibration energy. Each TMD consists of a spring-mass-damper system that resonates out of phase with the structural motion [13]. The application of TMDs on tall buildings around the world is summarized later in this paper. Furthermore, other types of dampers and their mechanism in the response mitigation of tall buildings have been discussed in this paper.

Another approach to reducing the wind load is aerodynamic shape modification of tall buildings. This is based on the fact that a bluff body's shape determines the aerodynamics of an object; as such, the shape is a critical consideration for the goal of reducing the wind loads on a structure. Due to its popularity, aerodynamic modification has gained a lot of attention in recent years among the wind engineering community. Wind tunnel experiments and Computational Fluid Dynamics (CFD) simulation are the two primary techniques to study the effectiveness of aerodynamic modification in wind load and response reduction. In this regard, investigations related to the aerodynamic modification of tall buildings using those two approaches are reviewed in this paper, and their results are discussed. Aerodynamic shape optimization has helped to reach optimum design for a building while minimizing the wind load. Past studies indicate that applying these algorithms along with high-fidelity CFD modeling can provide promising solutions to overcome the existing challenges in Atmospheric Boundary Layer (ABL) wind tunnel testing.

The increasing number of tall buildings in recent years and their susceptibility to wind-induced vibrations have encouraged the preparation of this state-of-the-art review on existing mitigation methodologies. The significance of this paper is that both auxiliary damping systems and aerodynamic modification of building cross sections are discussed. This provides a general framework for the mitigation of wind-induced vibration of tall buildings. This paper provides a comparative review of different types of control systems for wind-response applications and can be used as a point to commence from for future developments. The review provided here would inform those who are interested in finding scientific solutions to suppress the wind excitation of tall buildings by applying the most recent accomplishments in this area. The organization of this paper can be summarized as follows: Section 2 includes the mitigation approaches used to suppress or mitigate the undesired vibration of tall buildings. Section 3 reviews the existing aerodynamic shape modifications of tall buildings regarding the aerodynamic/aeroelastic load reduction.

2. Mitigation of wind-induced vibration

Tall buildings are prone to wind-induced vibration due to their flexibility, low inherent mechanical damping, slenderness, light structure, and the possibility of combined modes [14,15]. This type of vibration can also be found in other structures, such as structural cables [16–19]. The vibration can result in occupant discomfort in the form of annoyance, headache, or sickness, damage to nonstructural elements such as facade, and in some cases, damage to the structural system. To suppress this undesired vibration, a number of mitigation approaches have been proposed over the past decades that can be generally classified into active and passive control systems [20]. Fig. 3 demonstrates the flowchart of the most common existing mitigation approaches for wind-induced vibration of tall buildings. The application of a damping system in tall buildings is increasing over time because of the significant advances in recent cost-effective dampers, which are easily installed on a building. Columbia SeaFirst Building in Seattle, Washington, and Twin Towers (World Trade Center in New York), were the first buildings where a large number of viscoelastic dampers were used to control the building motion [21]. Since then, other types of viscoelastic dampers such as tuned mass dampers (TMDs), tuned sloshing dampers (TSDs), tuned liquid column dampers (TLCDs), active mass dampers (AMDs) are installed to suppress the building motion [22]. These control systems will be explained later in more detail.

2.1. Active control

Active vibration control is a technique to mitigate vibration by the application of an external force. Active vibration control of tall buildings can be achieved by changing the structural damping or stiffness using hydraulic or electro-mechanical actuator systems. The active vibration control system usually consists of three major components: (1) **sensors**, which measure the structural responses or excitation; (2) **controller**, which decides the action of actuators in an intelligent manner; (3) **actuators**, which execute command signal from controllers to control the unwanted vibration. Fig. 4 shows a diagram for these components. The control force applied to the structure by the actuators can be determined by the control algorithm and measured structural responses. Compared to passive control, active control is able to adjust to variations of parameters, which enables it to reduce the vibration of tall buildings for a wide frequency range in a varying external environment. Moreover, active control devices are capable of generating a controlling force in a controlled manner and a short period. As a result, active vibration control is considered more effective. The active vibration control of tall buildings can be accomplished through two different approaches: active mass damper and active tendons.

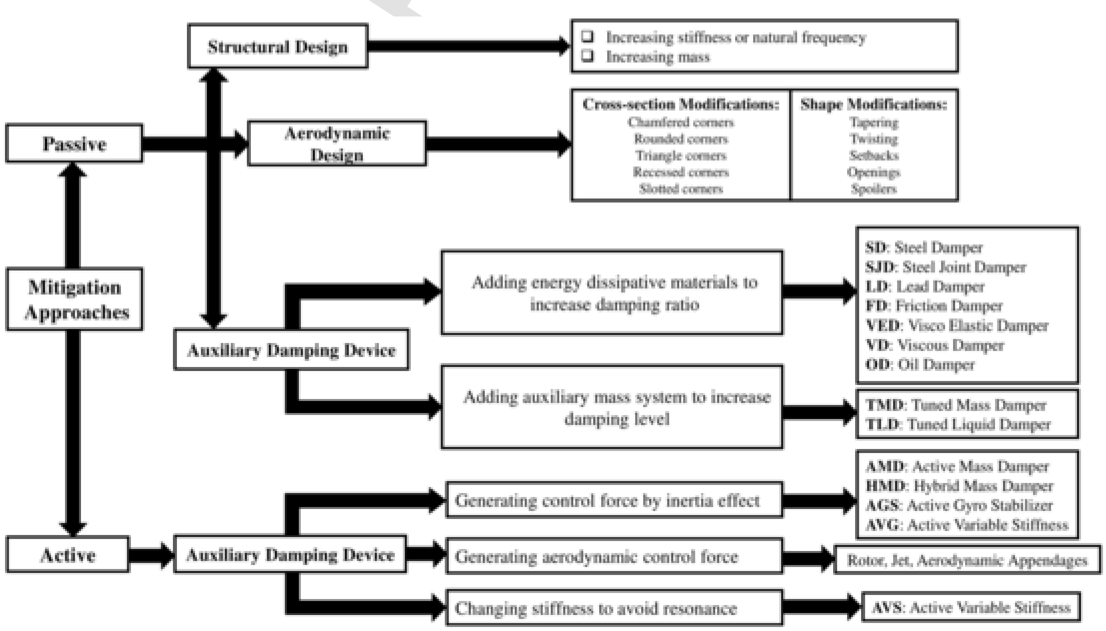

Fig. 3. Flowchart of mitigation approaches for tall buildings [23].

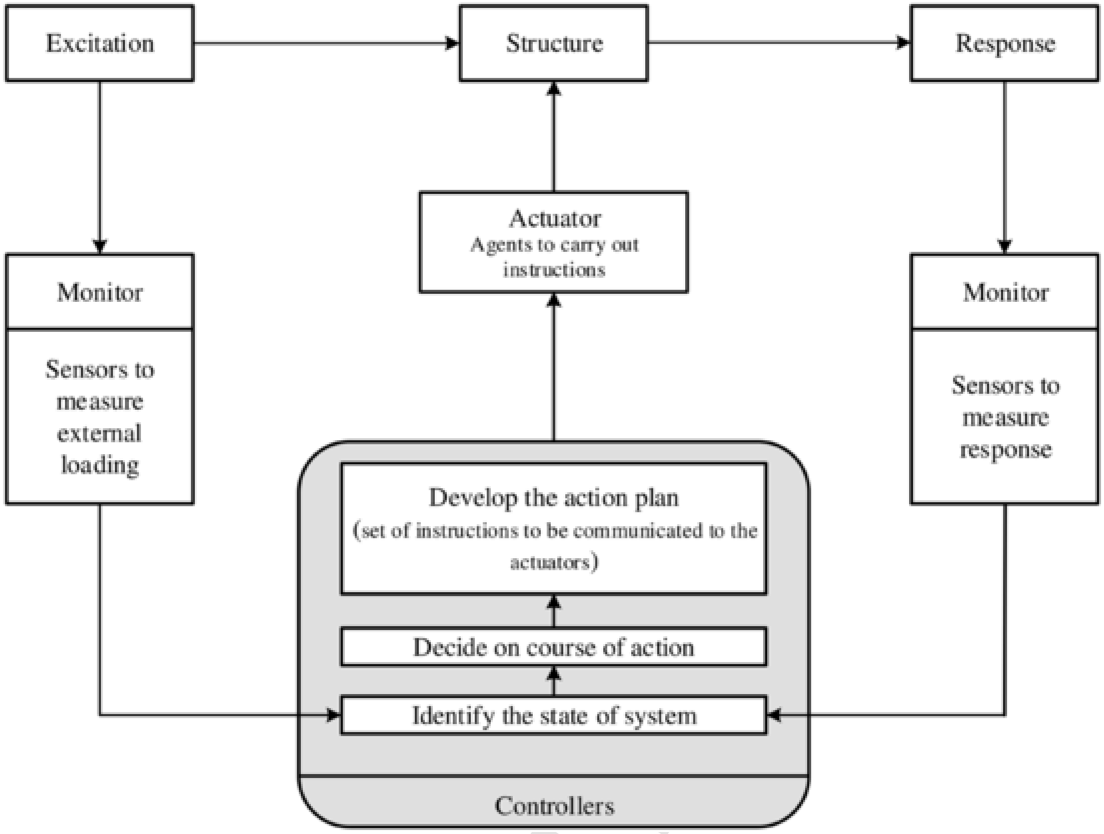

Fig. 4. Components of the active control system [24].

2.1.1. *Active damping*

Active Mass Dampers (AMD) system developed in the late 1980s, also known as Active Tuned Mass Damper (ATMD), usually consists of a secondary mass, which is attached to the primary system through an actuator. A control computer determines the control force based on the control algorithm and structural responses measured by sensors placed on tall buildings. The actuator drives the secondary mass with the computed force, either in sliding or pendulum form, to mitigate the vibration of tall buildings. An illustration of the AMD system is shown in Fig. 5. It has been found that AMD systems can reduce structural wind-induced response by up to 30–50% [23].

Despite the advantages, there are still some disadvantages for the AMD system. One of the most important concerns is that AMD may destabilize the structural system if the parameters change. Therefore, it is of vital importance to ensure the stability of the control systems. Various control algorithms have been studied to investigate their applicability to AMD systems. Abdel-Rohman [26] developed a process to design an effective ATMD to control the vibration of a tall building under random wind load. Wu and Yang [27] studied three control algorithms: Linear Quadratic Gaussian (LQG), H∞, and continuous Sliding Mode Control (SMC) strategies to find out their effectiveness on the mitigation of wind-induced vibration on the Nanjing TV transmission Tower. They found that all of these three algorithms are capable of reducing structural vibration. Yan et al. [28] used H_{rms} in conjunction with the GRG algorithm to obtain the optimal values of feedback controllers that determine the control force of the ATMD system under both along-wind and across-wind excitations. Ikeda et al. [29] investigated the performance of two ATMDs installed on a ten-story, steel-frame building in Tokyo. The system employed the LQR control algorithm to control the vibration in both lateral and torsional vibrations. It was found that the control system can reduce 33% in peak response subject to wind loadings. Since it is challenging to measure displacement and velocity directly for tall buildings and accelerometers are widely used to monitor the acceleration of tall buildings, it is necessary to develop an algorithm that employs an acceleration signal to control the vibration of tall buildings. Yang et al. [25] used the Negative Acceleration Feedback (NAF) control algorithm to generate displacement for the active mass from acceleration data. An analysis showed that the stable condition for NAF is static, and it can increase the damping of targeted mode without inducing instability. Talib et al. [30] designed a multi-input and multi-output feedback control system using AMD. The proposed control system utilizes multiple accelerometers and multiple active mass dampers to reduce vibration. The effectiveness of this system has been validated both theoretically and experimentally. Overall, it can be concluded that although the active dampers have the potential for destabilizing the system, they could be very efficient in dissipating the vibration energy of tall buildings if they are integrated with appropriate controlling algorithms.

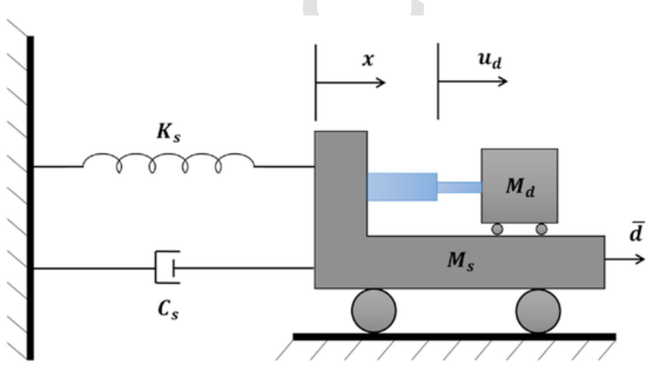

Fig. 5. Mechanism of the active mass damper [25].

2.1.2. Active tendons

Active tendons are pre-stressed cables, whose stress are controlled by actuators. Fig. 6 illustrates the active tendon control system. A tendon is fastened to a specific location of a tall building and then passed over pulleys to be connected to linear actuators. The tensile forces applied to tendons by actuators can suppress the wind-induced vibration of tall buildings.

Similar to the ATMD system, various control strategies have been proposed to control the building vibration using an active tendon system. However, the majorities of these algorithms are related to vibration control due to earthquakes. For example, Alli and Yakut [32] adopted the fuzzy sliding-mode control (FSMC) method for seismic isolation of earthquake-excited structures. Park et al. [31] used the fuzzy supervisory technique for the active control of earthquake-excited building structures. Park et al. [33] proposed a bilinear pole-shifting technique with H∞ control method to suppress the earthquake-excited vibration of tall buildings.

2.1.3. Semi-active control

Tall buildings usually require large control forces, in the order of mega newton, to effectively mitigate the wind-induced vibration. A fully active force actuator system needs to consume a lot of energy in order to generate the forces that are required to control the vibration of tall buildings. As a result, there are many studies carried out to design force actuators that have low energy demand. For this purpose, one approach was proposed to change the design of actuators such that only a little energy is required to change the device properties, such as damping and stiffness. Those devices are called semi-active control devices. The semi-active devices can dissipate vibration with low energy demand and hence are usually operated by batteries. Moreover, semi-active devices will not destabilize the system, whereas the active device may sometimes destabilize a system. Semi-active devices can be divided into four categories: Variable-Orifice Dampers, Variable-Stiffness Device, Controllable-Fluid Dampers, and Variable-Friction Dampers.

Variable-Orifice Dampers: Variable-orifice dampers use a controllable, electromechanical, variable-orifice valve to change the resistance to flow of a traditional hydraulic fluid damper. Fig. 7 shows the schematic of a variable-orifice damper. It consists of a fluid-filled cylinder, a piston, and a bypass valve, which is used to connect the two sides of the piston. By regulating the opening of the valve with a controller, the viscous flow filled in the cylinder can be controlled. As a consequence, the damping coefficient of the damper can be modified in real-time.

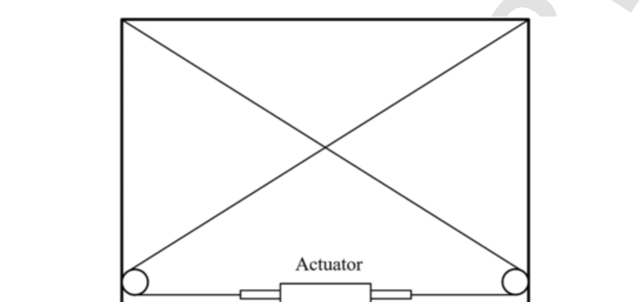

Fig. 6. Schematic view of an active tendon control system replotted from Ref. [31].

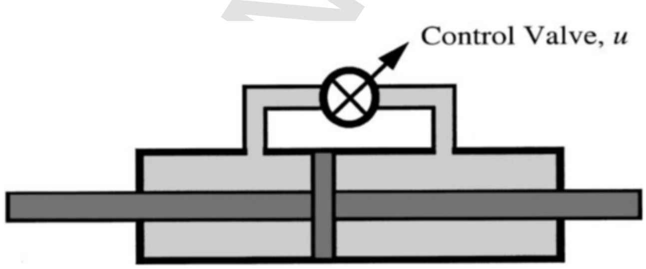

Fig. 7. Schematic of a variable orifice damper [34].

Variable-Stiffness Device: Variable-stiffness device is a type of stiffness element that can be turned on or off. It comes with the combination of variable-orifice dampers, in which the dampers can be switched on and off to lock or unlock the stiffness. Those dampers can also be termed as active variable stiffness (AVS) systems. Fig. 8 illustrates the mechanism of the AVS system. Tall buildings equipped with AVS system have to consider two independent stiffness systems, one is fixed and cannot be changed; the other is variable and can be switched on or off [24].

Controllable-Fluid Dampers: Controllable fluid refers to the types of fluid whose properties can be changed. Such fluid is usually a mixture of oil with ferric ion particles. As a result, dampers made of controllable fluid is able to alter their damping characteristics by changing the properties of the fluid. Two fluid are viable to be used for controllable-fluid dampers: (1) electrorheological (ER) fluids and (2) magnetorheological (MR) fluids. However, Spencer and Sain [35] pointed out that only MR dampers are suitable for civil structure applications. The essential characteristic of controllable fluids is that they can reversibly change from a linear viscous fluid into a semisolid with a controllable yield strength when a magnetic field is imposed [34]. Fig. 9 shows the schematic of the controllable-fluid damper. It can be seen from the figure that controllable-fluid damper is simpler than variable-orifice dampers or AVS as they adopt no valves or mechanisms that need maintenance. Therefore, controllable-fluid dampers are deemed as more reliable.

MR dampers can significantly outperform the passive damping devices with only a small fraction of energy required compared to active control devices. Zhu et al. [36] proposed a semi-active control strategy to mitigate the vibration of building structures under wind loading using MR/ER dampers. The optimal control method was developed based on the stochastic averaging method and the stochastic dynamic programming principle. The numerical simulation of a 40-story tall building demonstrated that displacement, inter-story drift, and acceleration could be reduced significantly. Wang et al. [37] designed semi-active tuned liquid column damper using magneto-rheological fluid (MR-TLCD), which combines the benefits of magneto-rheological smart materials and tuned liquid column dampers. The effectiveness of MR-TLCD damper was validated by a 50-story tall building under wind load-

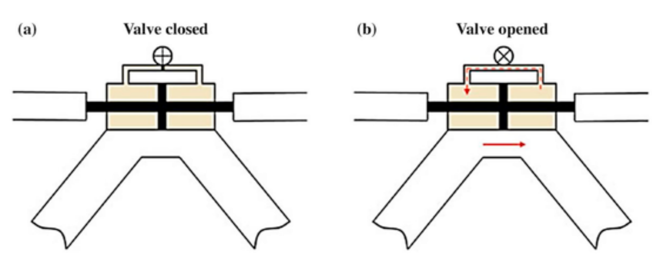

Fig. 8. Schematic of variable stiffness (a) locked, (b) unlocked [24].

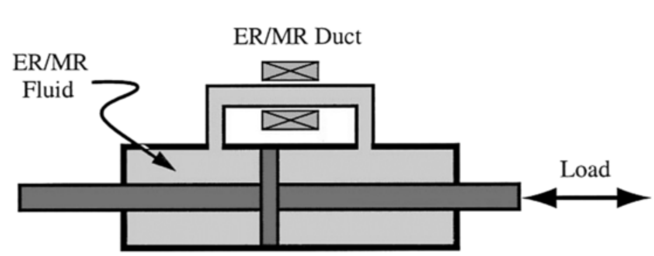

Fig. 9. Schematic of a controllable fluid damper [34].

ing. The results showed that MR-TLCDs with optimal parameters have better capability in the mitigation of wind-induced vibration than conventional TLCDs. Ni et al. [38] used the statistical linearization method and the optimal linear-quadratic (LQ) control strategy to reduce wind-induced vibration of tall buildings using MR-TLCD dampers. The classical linear-quadratic (LQ) control strategy is employed to determine the optimal control force of the dampers after the system is linearized. A case study of a 50-story tall building verified the efficiency of the proposed control method. Tse et al. [8] developed a system to suppress the wind-induced three-dimensional vibration using a bi-directional tuned mass damper (TMD) incorporating two magnetorheological (MR) dampers. The optimal force of MR dampers was calculated by the linear quadratic regulator (LQR) method to minimize the story accelerations. Aly et al. [39] presented a lever mechanism to enhance the performance of MR dampers, which were optimally installed in the building to reduce its wind-induced response in lateral directions. The proposed mechanism can enable the cases where inter-story drift is not sufficient for dampers to work effectively.

Variable-Friction Dampers: Variable-friction dampers utilize the friction force to dissipate vibrational energy in a structural system. The friction, which is delivered by the relative motion of two components in direct contact, can be adjusted by modifying the normal force applied to the components. The normal force can be changed by hydraulic, electromagnetic, and piezoelectric actuators. Fig. 10 shows two types of variable friction dampers.

A summary of past studies on active or semi-active dampers with the application of reducing the wind response in tall buildings is shown in Table 1.

2.2. Passive approach

Although the installation of damping systems is required to control the wind excitation of tall buildings, there are two passive approaches that can reduce the wind load through modification in the structural design and aerodynamic design. These two passive solutions are explained in the following sections.

2.2.1. Structural design

Mass and stiffness are two parameters that can be adjusted during the structural design procedure. Adding total mass to the system reduces the building's natural frequency ($n \sim \sqrt{K/M}$) which results in increasing the reduced velocity ($RV = U/nD$) and Scruton number ($Sc = m\zeta/\rho D^2$) at a given velocity. Additionally, since the vortex-induced response is inversely proportional to Sc, the wind-induced response mitigates due to the addition of mass to a building. Despite its advantages to reduce the wind response, increasing mass magnifies the construction costs and can increase the seismic load in seismic prone regions, which makes this solution impractical. The next approach is adding stiffness to the building structure leading to larger natural frequency and stiffer structure that can reduce the wind response by increasing the jerk components [22], but it has no influence on the building acceleration that is another design factor for tall buildings. Moreover, additional stiffness leads to extra construction costs while providing less interior space due to using larger structural columns. To maximize the stiffness of tall building, the supporting structure is placed on the perimeter while providing this stiffness through concrete and steel in columns with lower cost compared to thick beams. Notwithstanding the drawbacks of these two mitigation approaches, it is required to optimize the structural design for the minimization of both wind and earthquake loads.

2.2.2. Aerodynamic design

Another well-accepted approach aerodynamic shape modification to control the wind-induced vibration of a tall building is to change the cross section and/or overall shape along the height in order to disrupt the vortex formation around buildings that are mostly considered as bluff body structures. As shown in Fig. 2, there are several conventional ways to modify the building geometry, such as rounding/cutting corners, through openings, tapering, twisting, setbacks, and openings along the height to improve the aerodynamic performance of a tall building. The aerodynamic modification and optimization will be thoroughly discussed later in a separate section due to their high importance.

2.3. Passive control

Passive control is usually referred to those damping systems which do not need the sensors or actuators with any external power supply to dissipate the undesired energy causing vibration. The inherent mechanical damping mainly originates from material properties; therefore, structural designers cannot desirably control this quantity. However, external dampers can be used to provide the required total damping for suppression of wind-induced vibration. It should be noted that the building acceleration is inversely proportional to the square root of the damping ratio of the building. Auxiliary damping devices usually operate in active or passive form. They are classified into two groups based on their energy dissipation and system requirements named Indirect-Energy Dissipation (IED and Direct-Energy Dissipation (DED) [23]. These damping devices help attenuate the vibration caused by either wind or earthquake loads.

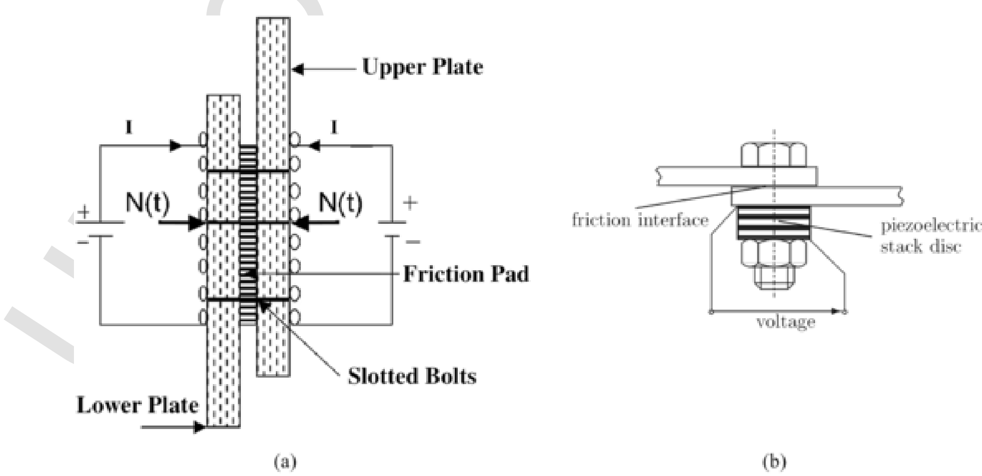

Fig. 10. Schematic of variable friction dampers.(a) electromagnetic friction damper [40](b) piezoelectric friction damper [41]

Table 1
Past studies on active damping system used for wind-induced vibration of tall buildings.

Reference	Control system	Remarks
Xu [42]	Active mass damper (AMD)	Wind response can be substantially decreased if acceleration sensors are employed, and the parameters of AMD are appropriately designed.
Xu et al. [43]	Active mass damper (AMD)	The proposed AMD driven by permanent magnet synchronous linear motors indicated that the damping ratio of first vibration mode could increase up to 11 times the original value.
Kim et al. [44]	Active mass damper (AMD)	The Along-wind response was alleviated efficiently by using an AMD and linear quadratic regulator.
Bani-Hani [45]	Semi-Active tuned mass damper (SATMD)	STMD can reduce the structural responses similar to an ATMD, but with a signifi cant reduction in power consumption. Experimenting on a 76-story building showed that STMD could mitigate the wind responses similar to an ATMD, but with consuming significantly less power.
Aly [46]	Active tuned mass damper (ATMD)	The building resilience was evaluated under extreme wind load by the installation of ATMD, and an incredible response reduction was reported in the lateral direction.
Ming [47]	Active mass damper (AMD)	A simple method was introduced to design ATMDs for high-rise buildings under wind load, and the numerical analysis proved its application to control the vibration.
Varadarajan, and Nagarajaiah [48]	Semi-Active Variable stiffness damper (SAVSD)	They proposed a method to retune the frequency continually due to real time control continuously. Compared to the uncontrolled building, this damper could reduce the response even when the building stiffness changes by ±15%.
Deshmukh and Chandiramani [49]	Semi-Active Variable stiffness damper (SAVSD)	Conducting a study by using linear and nonlinear models to adjust the stiffness resulted in providing acceptable response and acceleration control compared to active control.

2.3.1. IED auxiliary dampers

Since these auxiliary dampers require a secondary system for energy dissipation, they are called indirect energy dissipation dampers. As an example, attaching a spring and a damper to a structure to impede the building movement. Few important indirect-energy-dissipative auxiliary dampers are described as follows:

Tuned Mass Damper (TMD): This damping system has been the most popular type implemented in tall buildings. This system, also known as a harmonic absorber or seismic damper, includes an initial mass located at where the maximum response occurs through spring and viscous/viscoelastic dampers. The inertial force in this system is transmitted to the main structural frame, and the required damping depends on the ratio of damper's mass to the effective mass of building at the desired vibration mode [23]. The simplified mechanism of a TMD is shown in Fig. 11 through spring, damper, and lumped mass representing the original structure and damping device. TMDs have been widely installed on tall buildings, towers, and other structures to arrest the vibration. Two distinct parameters determining the effectiveness of TMDs are mass ratio (ratio of TMD mass to the generalized mass of building at desired vibration mode) and TMD mass displacement [50]. The largest simple-pendulum TMD in the world has been installed in the Taipei 101, Taiwan [51,52]. Table 2 summarizes the information of past TMDs used in tall buildings.

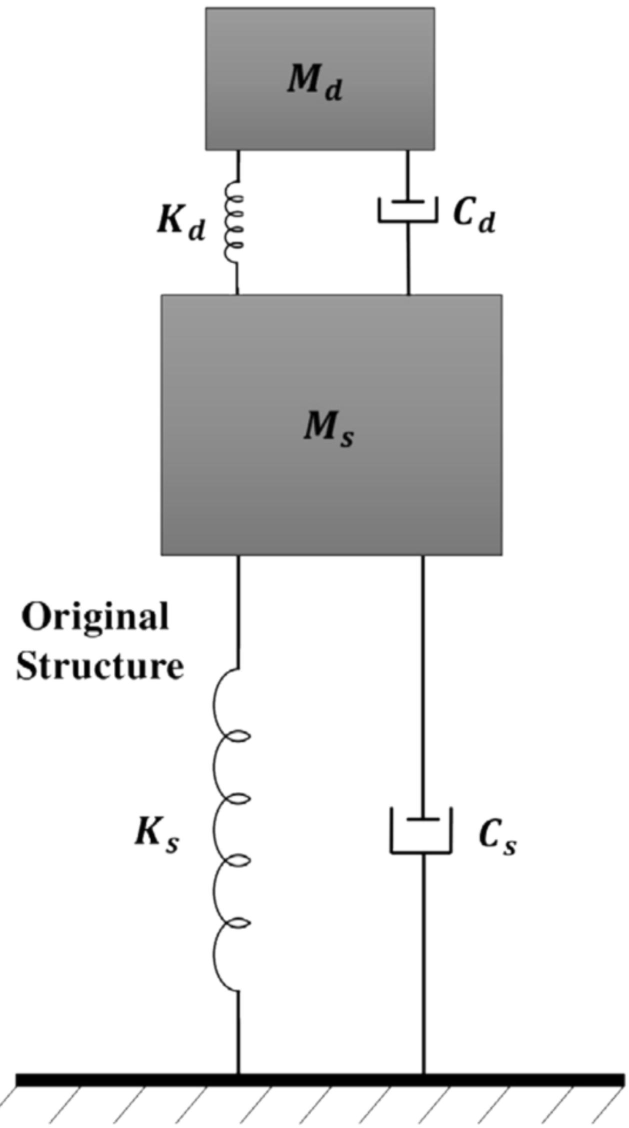

Fig. 11. Schematic view of a TMD system attached to the original structure replotted and simplified from Refs. [53].

Tuned Liquid Damper (TLD): The mechanism of this damper is similar to a TMD except that a liquid (usually water) is used instead of mass. This damping system was used first in the 1980s to suppress the building vibration [54–56], and Japan is a pioneer in using such a system in tall buildings. Tuned Sloshing Dampers (TSD) and Tuned Liquid Column Dampers (TLCDs) are two main subcategories of a TLD system [23]. The liquid in this damper plays an important role in damping the energy originated from external forces. TLDs and TMDs can reduce the dynamic response to 1/2 and 1/3 of the original response [57], but these dampers (TLDs) are not as common as TMDs. Compared with TMDs, TLDs have a lower initial cost and almost maintenance-free operation along with simplicity in construction and frequency tuning [50]. However, the disadvantages of this system include providing the nonlinear behavioral and additional mass to the building. Furthermore, the design of TLDs is more complicated than TMDs owing to nonlinear features. Fig. 12 illustrates the mechanism of a TLD using the liquid to damp the energy.

Combined Tuned Damper (CTD): Some advantages of the tuned liquid column dampers (TLCDs) such as easy installation, low cost, no maintenance, and no additional mass to the main structure have made these dampers an excellent choice to replace or combined with well-

Table 2
Application of TMDs in tall buildings [53].

Name	Weight (ton)	*n*(Hz)	Height (m)	No. Floors	Location	Year Completed	Damper Type
John Hancock	2 × 300	0.14	241	60	Boston, MA, USA	1976	4 TMD
Citycorp Center	370	0.16	278	59	New York, USA	1978	TMD
Kyobashi Center	5	–	33	11	Tokyo, Japan	1989	2TMD
Crystal Tower	540	0.24–0.28	157	37	Osaka, Japan	1990	PTMD
Shimizu Tech Lab	4.3	–	30	7	Tokyo, Japan	1990	TMD
ORC 2000 Symbol tower	200	0.21	188	50	Osaka, Japan	1992	2 ATMD
Applause Tower	480	–	162	34	Osaka, Japan	1992	1TMD
Sendagaya INTES	72	–	58	11	Tokyo, Japan	1992	2 TMD
Rokko Island Procter and Gamble	270	0.33–0.62	117	36	Kobe, Japan	1993	ATMD
Yokohama Landmark Tower	340	0.185	296	73	Yokohama City, Japan	1993	2TMD
Chifley Tower	400	–	209	53	Sydney, Australia	1993	1 TMD
C Office Tower	200	0.34	130	32	Tokyo, Japan	1993	ATMD
Ando Nishikicho	–	0.68–0.72	68	14	Tokyo, Japan	1993	TMD & ATMD
MKD8 Hikarigaoka	–	0.44	100	30	Tokyo, Japan	1993	ATMD
P&G Japan Headquarters	270	–	131	31	Kobe, Japan	1993	3 TMD
Shinjuku Park Tower	330		227	33	Tokyo, Japan	1994	3 ATMD
Building M		1.33 (x) 1.54 (y)	30	9	Osaka, Japan	1994	2TMD
Sea Hawk Hotel and Resort	132	–	143	36	Fukuoka, Japan	1995	TMD
Regensburg Siemens Building	0.17each	–	–	–	Regensburg, Germany	1996	11 TMD
Karlsruhe Building	0.55each	–	–	–	Karlsruhe, Germany	1997	24 TMD
Hotel Burj-Al-Arab (7-star)	11 × 5	0.8–2	321	60	Dubai, UAE	1997	11 TMD
Petronas Twin Towers	0.08 each	0.13, 0.17, 2.22	452	88	Kuala Lumpur, Malaysia	1997	12 TMD
Itoyama Tower	48	–	89	18	Tokyo, Japan	1997	1 TMD
TC Tower	100	–	348	85	Kau-Shon, Taiwan	1997	2 TMD
Otis Shibayama Test Tower	61	–	154	39	Chiba, Japan	1998	1 TMD
Century Pak Tower	440	–	170	54	Tokyo, Japan	1999	4 TMD
Shinagawa Intercity A	150	–	144	32	Tokyo, Japan	1999	2 TMD
Stakis Metropole	4.5	4.4	60	20	London, UK	2000	7 TMD
Cerulean Tower Tokyo Hotel	210	–	184	5	Tokyo, Japan	2001	2 TMD
Triton Square office complex	35each	–	195	–	Tokyo, Japan	2001	4 ATMD
Hotel Nikko Bayside Osaka	124	–	138	33	Osaka, Japan	2002	2 TMD
Dentsu New Headquarter	440	–	210	48	Tokyo, Japan	2002	4 TMD
Refab2	55each	–	–	–	Brazil	2003	4 TMD
Highcliff	–	–	252	73	Hong Kong, China	2003	TMD
Taipei 101	730	0.15	449	101	Taipei, Taiwan	2004	2 TMD
Bloomberg Tower	600	–	246	54	New York, USA	2004	TMD
Araucano Park	170	–	60	20	Santiago de Chile, Chile	2005	4 TMD
Comcast Center	1300	–	297	57	Philadelphia, PA, USA	2008	TMD
Shanghai World Financial Center	–	–	492	101	Shanghai, China	2008	ATMD
Al Mas Tower	2	1.6, 3.2	361	68	Dubai, UAE	2008	2 TMD
23 Marina	–	–	392	89	Dubai, UAE	2012	TMD
Shanghai Tower	–	–	632	128	Shanghai, China	2015	1TMD
432 Park Avenue	–	–	426	88	New York City, USA	2015	2TMD
Ping An Finance Center	–	–	599	115	Shenzhen, China	2017	2TMD

known tuned mass dampers (TMD) for dissipating the energy originated from either wind or earthquake forces [59]. To this end, the combined tuned damper (CTD), which is a combination of TMD and TLCD dampers, has been proposed to take advantage of both systems. In an experimental and analytical study by Matteo et al. [59], a novel control device was introduced for the installation of combined tuned dampers while distributing on different floors. Regarding the application of these dampers for wind excitation, Wang et al. [60] proposed a combined system to use the economic advantage of TLCDs and the high efficiency of TMDs. They found that the CTD system reaches its best performance when the CTD's frequency is tuned to the building frequency. This combined damping system revealed a satisfactory performance to damp out the vibration energy, which makes it an excellent replacement for the existing conventional systems. The number of researches on this system are limited so far, and further studies are required to fully investigate the performance of this combined system for wind and tornado-induced load acting on high-rise buildings.

Impact Damper (ID): In this system, a small rigid mass can freely move between two defined stops with optimal space in order to attenuate the structure response. The lumped mass, suspension length, and gap size are major design factors in this device. Although impact dampers are frequently used to reduce the vibration in turbine blades, printed circuit boards, and machine tools [61], they have been occasionally installed for rooftop masts in the past [62]. Fig. 13 demonstrates the mechanism of an impact damper.

Particle dampers (PD), which work based on a combination of impact and friction damping, dissipate the system energy by transferring it to a bed of particles. For more details about their mechanisms, the past review papers conducted by Gagnon et al. [63] and Lu et al. [64] are referred. In a comparative study by Lu et al. [65], it was found that a particle damper provides a broadband-frequency vibration con-

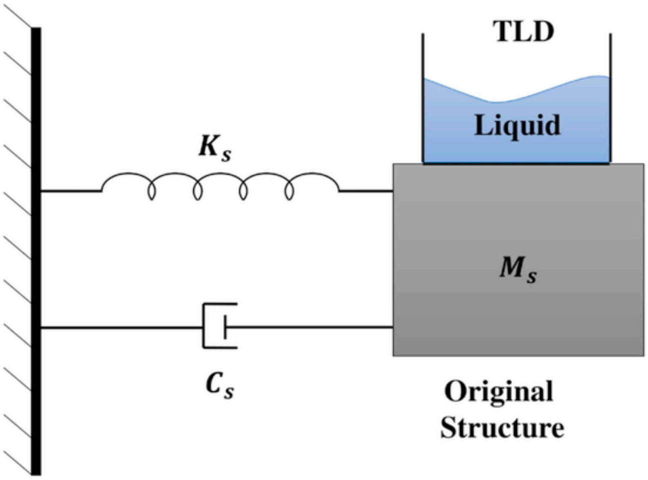

Fig. 12. Schematic view of a TLD damper attached to the original structure replotted from Ref. [58].

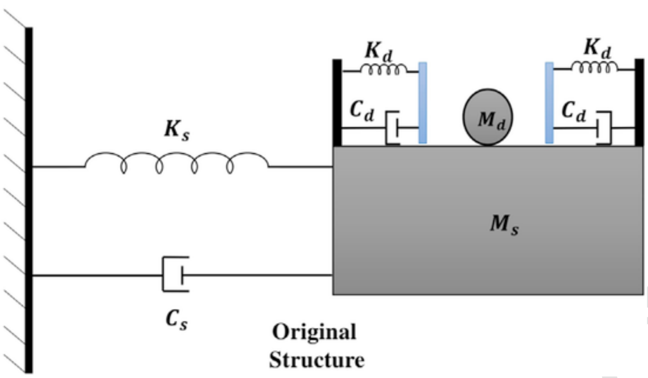

Fig. 13. Impact damper connected to the original structure in a single-degree-of-freedom system [23].

trol with better robustness than a TMD damper. Recently, particle tuned mass dampers (PTMD), which are the combination of the PD and TMD dampers, are designed to incorporate the advantages of both systems. Lu et al. [66] conducted an experimental and analytical study on the performance of PTMDs in response mitigation of tall buildings under broadband wind excitation. According to the results, they found that an optimum design for a PTMD system results in adding high positive damping to the building. In another study [67], a PTMD system was installed on a benchmark building, and a series of wind tunnel tests were performed to determine the influence of filling ratio and mass ratio. They observed a remarkable reduction in the building's wind response in special conditions. In another research, an experimental study was conducted by Lu et al. [68] to assess the influence of auxiliary mass ratio, particles' filling ratio, and particle density on the performance of PTMDs. They observed a massive reduction in the structural response due to the installation of a lightweight PTMD. Although there is a limited number of studies on mitigation of seismic-induced vibration of high-rise buildings through the installation of particle dampers or combined with other damping systems, further investigations are required to accurately assess the performance of PDs for high-rise buildings exposed to only extreme wind load.

2.3.2. DED auxiliary dampers

The overall damping can be increased by passive systems using direct energy mechanisms such as viscoelastic damper (VED), friction system (FS), and metallic dissipators (MD). This type of damper is becoming more and more popular because they occupy less space, can be easily attached to the existing structure, and has high efficiency in suppressing significant vibration. More information related to these systems is provided as follows:

Viscoelastic Damper (VED): Viscoelastic dampers are one of the earliest conventional damping systems that started in the early 1990s that are used to attenuate the structural response in high frequency and low-to-moderate vibration levels [69]. VEDs include steel plates and viscoelastic (VE) materials such as polymer or rubber that are installed between the metal plates regarding the energy dissipation of wind or other excitation sources. Fig. 14 shows the mechanism of a viscoelastic damper and the installation of steel and VE plates. Past studies indicated that these dampers increase the stiffness, leading to higher natural frequency while adding positive damping to the system [23]. Furthermore, the performance of these dampers depends on the vibration frequency and environmental temperature.

Metallic Dissipator (MD): Metallic dissipators, which are displacement-activated supplemental damping devices, damp the energy of structures while demonstrating hysteric behavior under cyclic loads. These dampers depend on yielding and inelastic deformation of components that can be flexure, shear, or axial deformation [70]. Existing MDs have different types, including the addition of damping or stiffness [71], torsional beam damper [72], lead extrusion device [73], buckling-restrained braces [74], U-shaped flexural plates (UFPs) [75], high force to volume damper [76], aluminum shear panels [77], cast steel yielding brace [21], shape memory alloys [78], buckling-restrained dry type dissipaters [79], buckling-restrained fused dissipaters [80], and self-centering buck-ling-restrained brace [81]. From the damping systems introduced here, shape-memory alloy (SMA) damper has gained considerable attention in the past for civil structures [82]. They have been used to dissipate the excitation energy produced in different structures such as bridge cable [83], power transmission line [84], and building [85]. These dampers use the shape-memory alloys, which are referred to those alloys that deform in cold conditions and then return to pre-deform shape when heated. Their application to mitigate the earthquake excitation of tall buildings has been investigated in several studies. In contrast, there is limited research on the implementation of these dampers for suppressing the wind-induced excitation of tall buildings. Xu and Cui [86] carried out a series of experiments to assess the impact of shape-memory alloy dampers in wind-originated energy dissipation, and they found these systems very useful. SMA dampers are sometimes integrated with other dampers, such as TMD, to take advantage of their unique properties. However, further studies are required in the future to focus on the application of these dampers for wind-induced vibration of tall buildings.

Friction Dampers (FD): The principle of these dampers is based on friction-induced by sliding surfaces, which can mitigate the response owing to the damping added to the system. They can be classified into two groups of rigid and braced frame friction dampers [23]. The first group, which can be replaced easily, provides plastic hinges, and

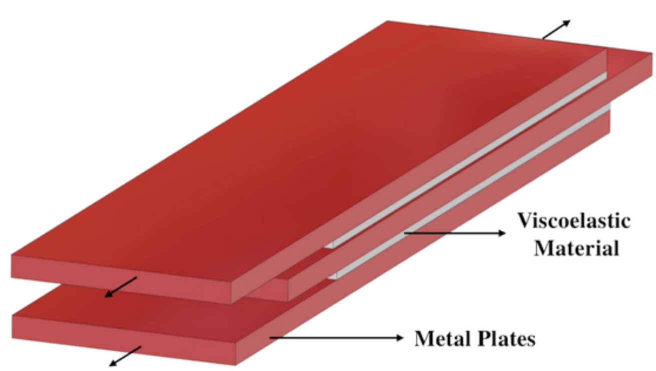

Fig. 14. Schematic view of viscoelastic dampers.

the second one uses the diagonal bracing while slipping after a certain stress level. They have a wide application for various structures and can be used to suppress the wind-induced response of tall buildings [87].

Viscous Damper (VD): These dampers, also known as the viscous fluid damper (VFD) or oil pressure Damper (OPD), work based on the resistance force originated from the fluid confined in the chamber, and the generated force is proportional to the relative piston velocity [23]. They are available in linear and non-linear forms. Fig. 15 shows the mechanism of a simple viscous damper with one piston. Some advantages of these devices involve low maintenance, attractive in the diagonal bracing system, excellent performance in the earthquake, and no need for external power.

Table 3 summarized some of the past research on wind-induced vibration mitigation of tall buildings by the installation of passive dampers.

3. Aerodynamic modification of tall buildings

The aerodynamic behavior of a bluff body, such as tall buildings, can be characterized by non-dimensional numbers that are briefly listed in Table 4. These important numbers describe the aerodynamic forces/moment as well as pressure distribution around a tall building. The primary goal of designers is to minimize the mean and/or fluctuation components of these variables to reduce the wind response of super-tall buildings. As shown in Table 4, all variables are a function of mean wind speed (U_H), and since the wind speed profile above the ground varies with height (see Fig. 16), these parameters change along the height of a tall building, which makes its aerodynamic behavior more complicated due to variation in loads, moments, Strouhal number, Reynolds number, and Scruton number. Amongst these parameters, there is no major concern related to Reynolds number because it is almost at the subcritical range, and it is assumed that the normalized aerodynamic forces are independent of Reynolds number and are almost constant, but St and Sc vary along with the height, which affects the vortex-induced response. Fig. 16 illustrates the turbulent intensity profile, wind speed profile, and incident angle or angle of attack (α) defined as the angle between X-axis and wind direction. Three significant parameters to study the wind-induced response of a tall building are mean drag coefficient (C_D), fluctuating lift coefficient (C_L') or non-zero mean lift coefficient at non-zero incident angles, and torsional moment (C_{MT}), as defined in Fig. 16.

Wind excitations cause vibration in the along- and/or across-wind directions that are originated from drag and lift forces, respectively. Conventional cross sections of tall buildings are sequentially square, triangle, and circle shape. Fig. 17 shows the vortex-shedding formation around these shapes and indicates that the lowest Strouhal number belongs to the square providing better vortex-shedding performance. Fig. 17 demonstrates how openings/through openings prevent the formation of large vortices at the wake that helps to not only stabilize the across-wind load but also decrease the drag force by reduction of wake area.

Apart from tall buildings, all vortex-shedding mitigation methods for circular cylinders are classified into three main groups listed as follows [104]:

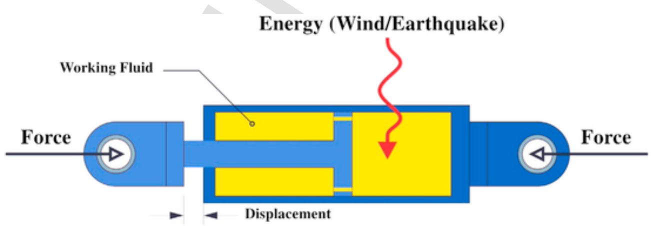

Fig. 15. Simple viscous damper exposed to external loads [88].

Table 3
Past studies on passive damping system used for wind-induced vibration of tall buildings.

Reference	Control system	Remarks
Momtaz et al. [89]	Tuned mass damper (TMD)	These dampers worked efficiently against both harmonic and non-harmonic excitations. They perform well (up to 70%) at high-frequency wind close to the building's natural frequency.
Xu et al. [90]	Tuned mass damper (TMD)	Wind tunnel experiments on a CAARC building proved the effectiveness of TMDs on wind response suppression. The study resulted in proposing an analytical model.
Kwok [91]	Tuned mass damper (TMD)	Full-scale measurement on wind-induced acceleration in Sydney Tower indicated these dampers increase the damping level in the first and second modes leading to suppression of wind excitation.
Kwok and Samali [92]	Tuned mass damper (TMD)	Conducting a parametric study to find an optimum TMD showed that these dampers could mitigate the wind response by 40%–50%.
Elias and Matsagar [13]	Tuned mass damper (TMD)	Tuning frequencies, placement, damping, and mass ratios were studied; it was found that the location of TMDs in buildings is very important to adjust the damping level.
Wakahara et al. [93]	Tuned liquid damper (TLD)	A significant reduction for the wind-induced response of the tall building was observed after the installation of TLD.
Wakahara et al. [94]	Tuned liquid damper (TLD)	A 50% reduction in response was reported after using TLD for a tall building in a full-scale measurement.
Chang and Gu [95]	Tuned liquid damper (TLD)	They showed the effectiveness of TLDs on mitigation of vortex-induced vibration of tall buildings through a series of wind tunnel experiments.
Liu et al. [96]	Tuned liquid column damper (TLCD)	The significant reduction in wind response was reported based on an analytical and experimental study on the effect of TLCDs on wind excitation.
Min et al. [97]	Tuned liquid column damper (TLCD)	It was concluded that TLCD is a cost-effective device for attenuating tall building vibration induced by wind load.
Lu et al. [66]	Particle tuned mass damper (PTMD)	From experimental and analytical analyses, the effects of particle material, total auxiliary mass ratio, mass ratio between container and particles, suspending length, and wind velocity were studied. High performance occurs at an optimum design.
Lu et al. [67]	Particle tuned mass damper (PTMD)	Robustness of these dampers was tested using wind tunnel experiments on an aeroelastic high-rise building. Particle filling ratio was the most significant parameter in adjusting the damping.
Lu et al. [68]	Particle tuned mass damper (PTMD)	They proposed a couple of guidelines for design and optimizing these dampers. The filling ratio of particles played an important role in designing PTMDs.
Xiaoming et al. [98]	Viscoelastic damper (VED)	The increase in the damping level of a 50-story building was studied in the extreme wind by the installation of a VED.
Samali and Kwok [99]	Viscoelastic damper (VED)	The application and positive performance of the viscoelastic damper to dissipate the energy in wind excitation was presented.
Xu and Peipei [86]	Shape-memory alloy damper (SMAD)	The use of these dampers was tested for a tall building through a comparative study and showed a significant reduction in wind response.

Table 3 (*Continued*)

Reference	Control system	Remarks
Peipei and Xu [100]	Shape-memory alloy damper (SMAD)	From an experiment, it was found that the control effects of SMA attenuator will be increased by increasing the rigidity ratio and reducing the yield displacement ratio.
Xu et al. [101]	Friction dampers (FD)	They proved that semi-active friction dampers using piezoelectric could suppress not only the displacement but also velocity and acceleration of a tall building.
Dong and Fan [102]	Friction dampers (FD)	Testing smart piezoelectric friction damper for a tall building showed a considerable reduction in wind response. The robustness of different control systems was also compared.
Chen et al. [103]	Fluid viscous damper (FVD)	To investigate the effectiveness of FVDs on suppression of wind response, a comparative was conducted through the Newmark method, KR-alpha method, energy-based linearization method, and statistical linearization method.

Table 4
Common dimensionless numbers to study the aerodynamics of a tall building.

Non-dimensional Number	Definition	Variable	Description
Reynolds number	$Re = \frac{\rho U_H D}{\mu}$	B	Width (m)
		D	Depth (m)
Strouhal number	$St = \frac{f_s B}{U_H}$	H	Height (m)
		U_H	Mean wind speed (m/s)
Drag coefficient	$C_D = \frac{F_D}{0.5\rho U_H^2 BH}$	f_s	Vortex-shedding frequency (Hz)
		ρ	Fluid density (kg/m ^{3})
Lift coefficient	$C_L = \frac{F_L}{0.5\rho U_H^2 BH}$	μ	Dynamic viscosity of fluid (kg/m·s)
		F_D	Drag force (N)
Moment coefficient	$C_{MT} = \frac{M_z}{0.5\rho U_H^2 BH^2}$	F_L	Lift force (N)
		M_Z	Moment (N.m)
Pressure coefficient	$Cp = \frac{P - P_{st}}{0.5\rho U_H^2}$	P	Surface Pressure (Pa)
		P_{st}	Static pressure (Pa)

- **Surface Protrusions**: interrupting the separation lines and/or shear layers, for instance: helical strakes, wire, fins, studs, or spheres.
- **Shrouds**: affecting the entertainment layer, e.g., perforated gauze, axial-rod, and axial-slat.
- **Nearwake Stabilizers**: preventing the interaction of entertainment layers on the surface, for example, splitter, plate, guiding vanes, based-bleed, and slit-cut.

Although the auxiliary damping devices can be used to mitigate or suppress the wind-induced vibration of tall buildings, there are significant concerns related to their applications, such as maintenance cost and regular inspection. However, the vortex-induced loads still exist even by attaching external dampers, and the problem is not permanently solved for this structure. Therefore, it is required to modify the building's outer shape in order to mitigate the vortex formation in the wake and disrupt the generation of coherent vortices along the height by changing the flow characteristics around a tall building. In this regard, there are two major types of aerodynamic modifications that are classified as cross section or minor modification and overall shape or major modification. The minor type that changes the overall cross-sectional shape of a tall building to reduce the strength of vortex shedding is listed as rounded, chamfered, and recessed corners, whereas major modification that adjusts the overall building outer shape to disorganize the vortex-shedding formation along the height can be listed as tapering, twisting, opening, and setbacks. In the following sections, the application and effects of these aerodynamic modifications on the wind-induced response of tall buildings are thoroughly discussed.

3.1. Cross-section and shape modifications

To modify the buffeting load that could originate even from surrounding buildings, it is required to conduct a significant change in the building shape. To reduction the buffeting load, it is necessary to design the buildings with a more streamlined shape. On the other hand, self-induced vortex shedding loads can be alleviated through modifications in the building's basic plan shape or more three-dimensional design on the upper level. The most common cross sections adopted in designing a tall building are square and triangle shapes because of their aerodynamic or structural privileges compared with other shapes. Figs. 18 and 19 indicate a few well-known cross section (minor) modifications applied on square and triangle shapes, respectively. Past studies have shown that these aerodynamic modifications are beneficial to reduce wind-induced responses in either along or across-wind direction. These modifications demonstrate that the corners are the most influential parts to improve the aerodynamic performance of a tall building. Apart from the mentioned modifications, some studies indicate that the aspect ratio of tall buildings is another parameter that influences the wind characteristics through the pressure distribution change around these gigantic structures [106,107]. However, the aspect ratio may not be considered a practical solution for aerodynamic modification of existing or new tall buildings because of the economic restrictions defining the required number of floors for more profit.

Another modification is to change the overall building shape as shown in Fig. 20. It can be seen that the straight square buildings are the simplest but most critical design due to blocking the airflow and a sudden separation of wind flow at sharp edges. As a result, if the building width (B) is not long enough to reattach the flow, a large wake area emerges behind the building, which increases the drag force and generates more instabilities because of vortex shedding. Tapering and setbacks are typically used to generate incoherence vortices along the height by varying the width length leading to variation of vortex-shedding frequency ($f_s = StU_H(z)/B$). Another advantage of this design is to linearize the mass distribution rather than uniform, which would reduce the earthquake loads as well. Changing the cross section along the height has a similar effect to forcing the vortices to shed over a more extensive frequency range. According to the wind rose diagram obtained at a specific location, the strongest wind direction may occur at one, two, or more angles; therefore, twisting the building gives this flexibility to designers to adjust the building orientation based on the wind rose diagram. Furthermore, twisting modification helps mitigate the vortex-shedding effect because of changing the incident angle along the height as a result of the twist angle. Spoilers are typically attached to the outside walls to disrupt the vortex formation, and this method has also been applied to other mechanical or aerospace structures such as aircraft wing. Another aerodynamic modification displayed in

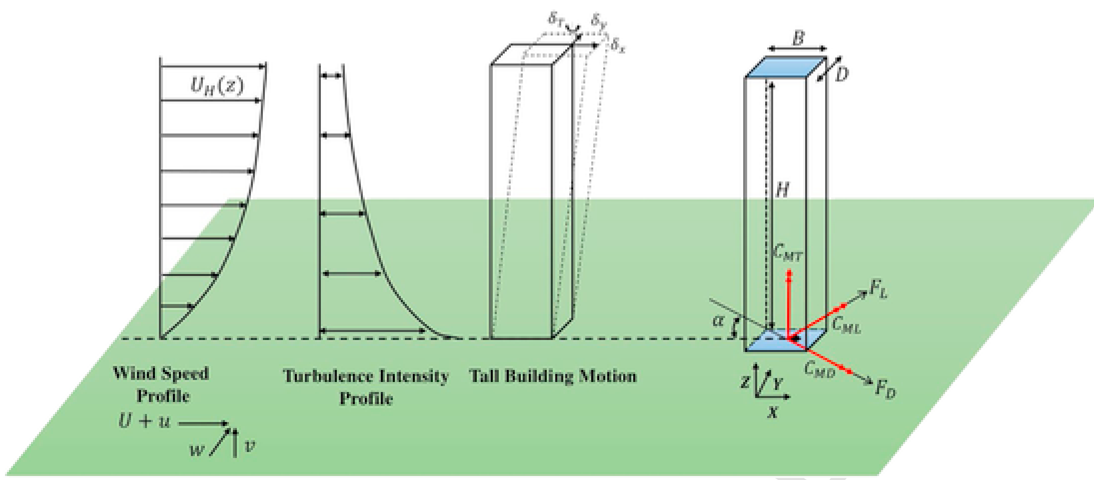

Fig. 16. Variation of wind speed and turbulence intensity in the Atmospheric Boundary Layer (ABL) and aerodynamic quantities.

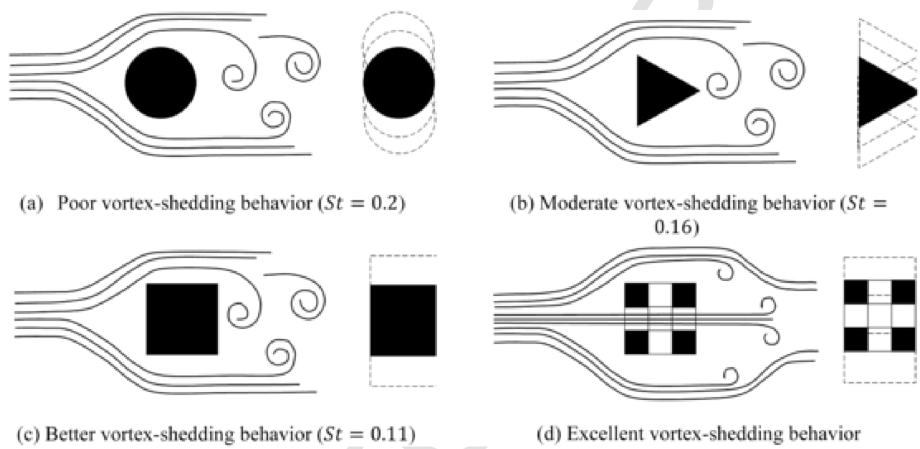

Fig. 17. Comparison of vortex-shedding performance of tall buildings with circle, square, and triangle cross sections [105].

Fig. 20 is to design a few openings on the upper part of a tall building to avoid the formation of vortices behind the building by blowing the airflow through these openings. Past studies showed that although a combination of aforementioned major and minor modifications is more advantageous than only one approach, the structural design limitation, material cost, and construction difficulties are necessary to be considered along with these aerodynamic modifications before the final decision.

A couple of important research are listed in Table 5 to remark the past accomplishments on major and minor aerodynamic modifications of tall buildings.

3.1.1. Wind tunnel experiments

In comprehensive research, the effects of these aerodynamic modifications were studied by performing wind tunnel experiments, and the results are presented in Figs. 21–26. All tall building configurations experimentally tested for a suburban area (power-law index of 0.27) are shown in Fig. 21. They include different major and minor modifications such as twisting, tapering, openings, setbacks, chamfered corners, and corner cut. Fig. 22 shows the mean and fluctuating overturning moment (otm) coefficients along- and across-wind directions for incident angles (α) ranging from 0° to 90°. The results indicate that the peak value of the mean drag moment (C_{MD}) for most cases occurs at the incident angles of 0°, 45°, and 90° while the peak value (absolute) of mean and fluctuating lift moments (C_{MD}, C'_{ML}) mostly happens at 45°, 75°, and 0°, 90°, respectively. Fig. 24 presents the results of mean and fluctuating drag, lift, and torsional moments along the normalized height for different building models. For mean drag and torsional moments, the results almost show a linear trend while the value of fluctuating moments is constant or uniform. For mean and fluctuating lift moments, it is observed that the variation is not linear or uniform, and the maximum value happens at z/H =0.7. Moreover, it can be seen that the straight square generates the maximum moments at a given elevation (z/H). In Fig. 24, maximum mean and fluctuating overturning moments are compared with the bar graph. This comparison shows that the maximum value belongs to square, rectangular, and inverse tapered models. In contrast, the tapered, twisted, and setback models have the lowest values for mean and fluctuating components.

To determine only the effect of twist angle (θ), the results of mean and fluctuating overturning moments along with peak values and bandwidth of power spectral density (PSD) are compared for different models with different twist angles in Fig. 25. It can be seen that the force moments are obviously reduced with increasing twist angles up to 180°, but they do not significantly change beyond $\theta = 180°$. Another important graph comparing the variations of Strouhal number along the normalized height is plotted in Fig. 26. This figure noticeably demonstrates the effect of tapering and setbacks in changing the vortex-shedding frequency or Strouhal number along the height that is extremely helpful to mitigate the across-wind response. As shown in Fig. 26, the Strouhal number does not notably change for square, corner cut, chamfered corner, and twisted models, but the models with setbacks incredibility increase the Strouhal number (around 200%) and tapering provides an excellent variation in Strouhal number (around 150%).

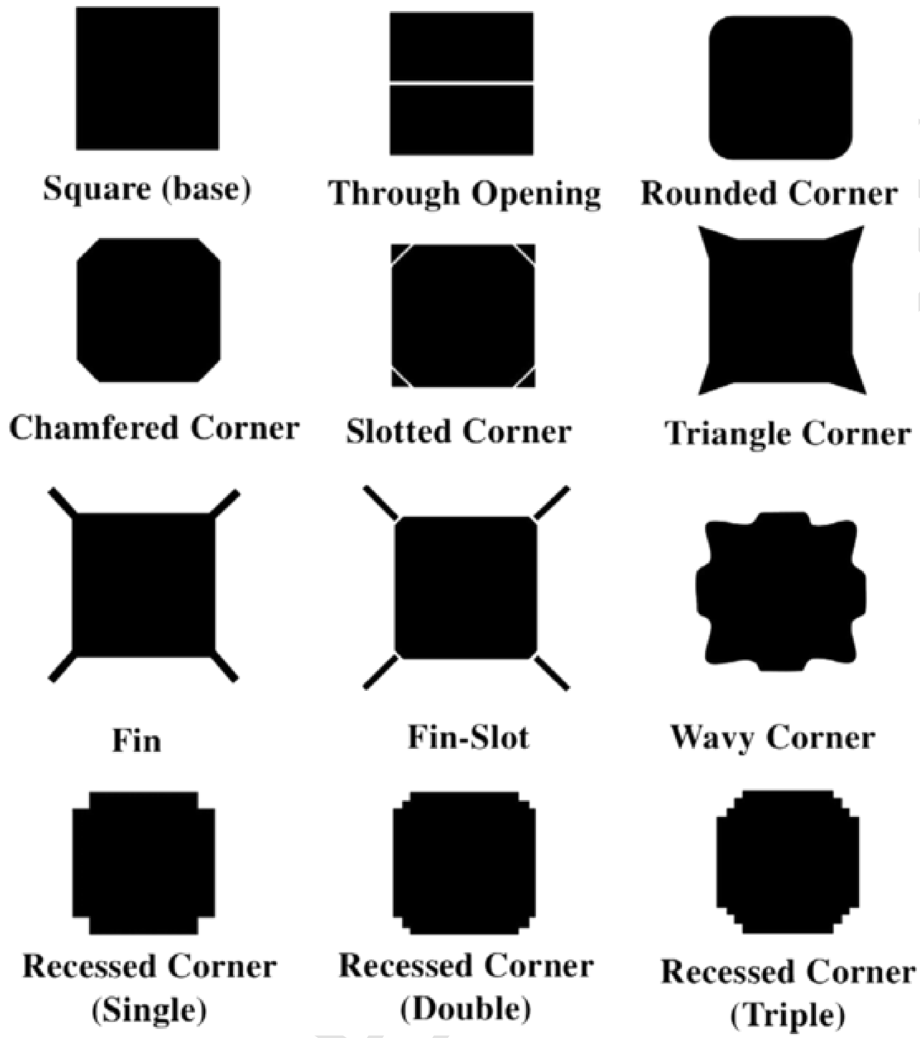

Fig. 18. Effective modifications to improve the aerodynamic performance of a tall building with the square cross section.

Although the across-wind response is not a concern for low-rise buildings, past studies showed that the across-wind response could become even larger than the along-wind response in a tall building. Gu an Quan [133] studied 15 scaled models representing the tall buildings by measuring the wind loads with wind tunnel tests. He investigated the effects of terrain type, aspect ratio, side ratio, and corner modification on the across-wind response of a tall building. Tamura et al. [134] evaluated the aerodynamic performance of 45 tall building models using wind tunnel experiments. These models included square, rectangular, and elliptic cross sections with corner cut, corner chamfered, tilted, tapering, inversed tapering, setback, twisting, and opening modifications. The results demonstrated that the combination of various modifications was more effective than only a single modification on the aerodynamic performance of a tall building. Wind tunnel experiments were used in another study to evaluate the aerodynamic performance of a few modifications on wind-induced response [116]. The results indicated that attaching small fins or vented fins to a square building increase the along-wind response, but the across-wind response was reduced for a specific range of reduced velocity. Moreover, the experimental results of a building with slotted corners showed a considerable reduction in along- and across-wind responses. Tamura and Miyagi [117] experimentally captured the mean and fluctuating components of wind loads in smooth and homogenous turbulent flow to study the influence of turbulence on the aerodynamics of square tall buildings with different corner shapes. The chamfered and rounded corners resulted in a reduction in drag coefficient, and the slope of lift coefficient ($\frac{dC_L}{d\alpha}$) with respect to wind angle of attack (incident angle) was positive at $\alpha = 0^{\circ}$ in the turbulent flow while showed a larger peak for power spectrum compared with a smooth flow. In another study [135], it was shown that increasing turbulent flow can help to reduce the drag coefficient of a rectangular cylinder, but it requires a large aspect ratio ($\frac{L}{D}$ =length/diameter) to avoid edge effects. Hayashida and Iwasa [114] explored the effect of the super-tall building's cross section on the vortex-induced response by performing wind tunnel tests. They studied eight models with different cross sections and reported the aerodynamic coefficients and dynamic response for all cases.

Kim et al. [124] measured the across-wind response of an aeroelastic tapered model to evaluate the influence of tapering on the dynamic response of a tall building. They carried out their experiments for one straight square model and three aeroelastic models with taper ratios of 5%, 10%, and 15%. They concluded that the tapering could be effective at high reduced velocity and moderate structural damping ratios (2–4%), but the across-wind response may increase when the damping ratio is very low. Kim et al. [136] performed a number of wind tunnel experiments to study the effect of increasing side in the cross section of a straight and twisted (helical) tall building on its aerodynamic performance. They measured the aerodynamic coefficients for tall buildings with triangle, square, pentagon, hexagon, octagon, dodecagon, and circular cross sections. The results indicated that increasing the number

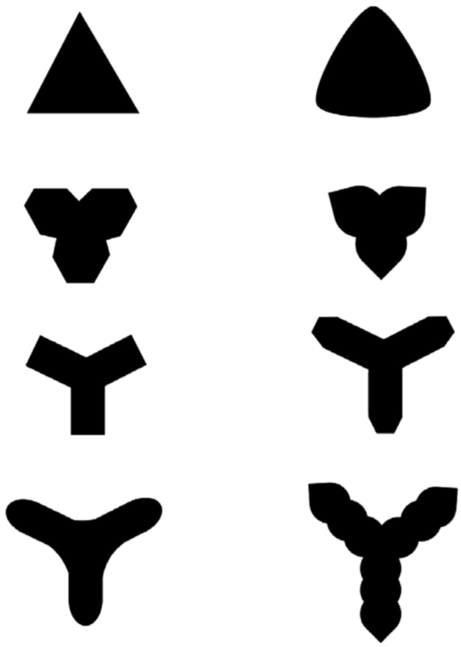

Fig. 19. Modified cross sections of a tall building with a triangle section as the base shape.

of sides decreases the overturning moment coefficient and spectral values and also found that the straight triangle cross section has the largest mean and fluctuating overturning moment while the most significant spectral value belongs to the straight square building. Furthermore, the twisting effect was diminished for models with more sides. Kim and You [123] reproduced the Atmospheric Boundary Layer (ABL) wind profile for suburban and urban terrain to study specifically the influence of taper ratio on aerodynamic instability of tall buildings. The tested models included a straight square model and three tapered models with taper ratios of 5%, 10%, and 15%. They found that tapering modification has a higher impact in a suburban area compared with an urban area, and also tapering reduces the across-wind response more than the other direction.

Moreover, the dynamic response of tapered models was not always lower than square buildings because of its dependency on wind angle of attack. Kim et al. [129] performed a series of wind tunnel tests to study the aerodynamic characteristics of tall buildings with a square plan and compared them with models with setbacks and tapering. The along-wind and torsional accelerations of tapered and setback models had a lower value than the square building while they had larger across-wind responses than the square model. Kim and Kanda [128] measured the pressure distribution at different building heights to study the pressure fluctuations and reported the Strouhal number to various heights for the tapered, setback, and straight models. They observed a significant contribution for the tapered and setback models on the power spectral density bandwidth and the Strouhal number at each height. Kim et al. [137] recorded the along- and across-wind loads along with the torsional load by measuring the surface pressure on 13 atypical buildings to determine the load combination. They proposed a method to accurately combine all wind loads while the maximum loads may happen at different times and locations. Kim and Kanda [131] carried out another research on measuring the pressure distribution around a tall building using wind tunnel tests to study the mechanisms of aerodynamic force mitigation. They selected three tapered, setback, and straight square models for their experiments while reproducing the Atmospheric Boundary Layer (ABL) wind profile for suburban and urban areas. The results demonstrated that tapering and setback reduced the mean drag and fluctuating lift forces, and increasing the taper ratio directly helps in mean drag force reduction while setback modification was more effective in decreasing the fluctuating lift force. Kim et al. [138] performed a series of wind tunnel tests on 13 scaled models representing the tall building to compare the aerodynamic performance

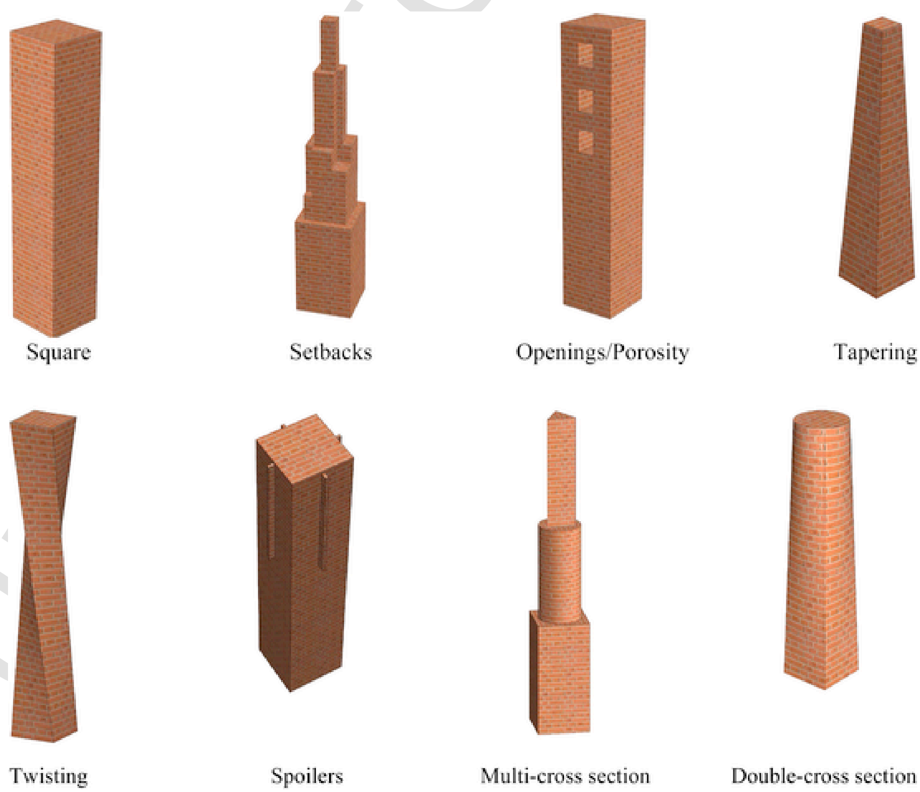

Fig. 20. Typical shape (major) modifications applied to tall buildings.

Table 5
Summary of past studies on major and minor aerodynamic modifications of tall buildings [108].

Reference	Minor	
	Modification	Remarks
Gu and Quan [109,110]	Chamfering, recession	They studied the aerodynamic damping in across-wind direction and derived a couple of formula for across-wind force PSD, moment coefficient, and shear forces
Kwok [111], Kwok et al. [112]	Chamfering, corner slots, horizontal slots	It was observed they have a considerable impact on along-wind and across-wind responses.
Tamura et al. [113]	Chamfering, rounding	They decreased the wind response in both directions.
Hayashida and Iwasa [114]	Triangular, circular, Y-shape with Corner cut rounding and surface roughness	They found that variation in the cross-section shape manipulates the damping.
Miyashita et al. [115]	Chamfering, recession, openings along height	A reduction in fluctuating force component along across-wind direction was observed for the normal incidence angle.
Kwok and Bailey [116]	Vertical fins, vented fins, corner slots	While slot corner influences on both directions, fins increase along-wind response and reduce the across-wind response.
Tamura and Miyagi [117]	Chamfering, rounding	A significant reduction in along-wind forces was observed.
Kawai [118]	Chamfering, recession, rounding	Corner rounding has more effect on aerodynamic modification than chamfering and recession.
Zhengwei et al. [119]	Single and double recession	Both mitigated the moment and torque coefficients; 7.5% recession ratio was most effective.
Tse et al. [120]	Chamfering, recession	For small modification lengths, the chamfered is less effective than the recessed corner.
Elshaer et al. [121]	Corner configurations	mean along-wind and fluctuating across-wind forces can be reduced for optimum design.
Major		
Deng et al. [122]	2.2%, 4.4%, 6.6% tapered	Increasing the tapering ratio causes more reduction in response.
Kim and You [123]	5%, 10%, 15% tapered	For across-wind direction than along-wind direction, tapering has more influence, while response reduction may not always reach.
Kim et al. [124]	5%, 10%, 15% tapered	Tapering is helpful at high reduced frequencies with a moderate damping ratio, but it causes a response increase for very low damping and high-velocity cases.
Dutton and Isyumov [125]	Opening	They observed a reduction in across-wind and a large reduction for gap d/D = 4%.
Kim and Kanda [126]	5%, 10% tapered and setback	Mean drag and fluctuating lift forces decrease considerably.
Bandi et al. [127]	60°, 180°, 360° helical	A decrease of max mean and fluctuating OTM coefficients in both directions was captured.
Kim and Kanda [128]	5%, 10% tapered and setback	They found that vortex shedding occurs more in the upper region of the building, and the vortex formation height moves upward.
Kim et al. [129]	5%, 10% tapered and setback	It was found that modified models with mass center and rigidity center eccentricity reduce along the wind and torsional accelerations, but across-wind acceleration is high. The more eccentricity exists, the more decrease in across-wind acceleration and increase torsional acceleration.
Kim et al. [130]	10% tapered	Wind responses of the tapered model are decreased for low turbulence and urban flow environment.
Kim and Kanda [131]	5%, 10% tapered and setback	Set-back modification mitigates response more than tapering. They observed a reduction in mean along-wind and fluctuating across-wind forces.

of different super tall buildings. They measured the wind forces on each floor and observed the largest peak of normal stress belongs to a straight square model, whereas the setback model had the least peak of normal stress. Furthermore, it was found that the bending moment in the along-wind direction had the most contribution, while the torsional moment was negligible compared with other moments. Kim et al. [139] conducted a comparative study to evaluate the effect of different modifications on wind excitation of high-rise buildings. They observed an improvement through increasing the twist angle for helical buildings and the number of sides for polygon buildings. They found the twist angle of 180◦ and five sides (pentagon) as the optimum parameters for aerodynamic modification.

Miyashita et al. [115] studied the effect of chamfered corners and openings on the wind loads acting on a tall building with the square cross section. Wind tunnel experiments were conducted to measure the aerodynamic forces and dynamic responses in both directions. They observed less fluctuating wind loads for models with corner cut or openings compared with a straight square model at zero incident angle. Furthermore, the along- and across wind response showed an elliptical orbit while the vibration amplitude in across-wind direction was larger. Unsteady wind loads were measured at different reduced velocities by Cooper et al. [140] for a tapered model with beveled corners, and the recorded dynamic response in time history helped to extract aerodynamic damping in the along- and across wind directions. They observed positive aerodynamic damping at the reduced velocity of 7.8 in the first vibration mode associated with the across-wind direction. The unstable aerodynamic damping of the tapered model with beveled corner had a lower value compared with the straight square model. Davenport [141] presented the experimental results for six scaled models representing the super-tall buildings by performing wind tunnel tests. Furthermore, the dependency of response on PSD and damping terms were discussed while explaining the shape effect on the aerodynamic performance of tall buildings. Dutton and Isyumov [125] explored the influence of through-openings on aerodynamic performance by wind tunnel measurements. They found that the across-wind response can be mitigated by gaps due to the disruption of organized or narrowband vortex shedding, which highly depends on the gap size. Bandi et al. [142] studied the pressure distribution over 26 scaled tall buildings with different cross sections and shapes by conducting a series of wind tunnel experiments. The cross section included triangle, square, pentagon, hexagon, octagon, dodecagon, circular, and clover. They investigated the effect of cross section and twist angle on the peak pressure at different wind directions and showed that aerodynamic performance of a tall building is highly dependent on these two factors. Amongst all configurations, they observed a significant reduction in peak pressure (Cp_{max}) for models with a twist and cornet cut. In another set of experiments [127], they studied the aerodynamic behavior of tall buildings with different configurations including straight triangle, clover, corner

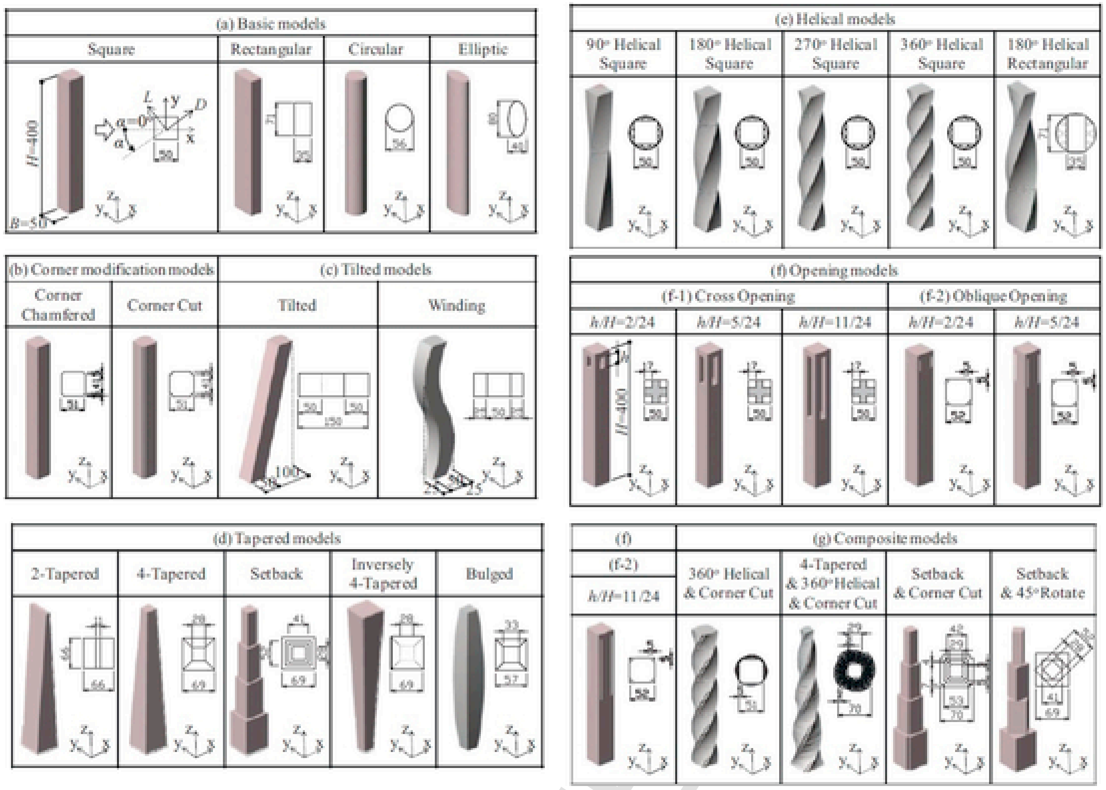

Fig. 21. Configuration of tested models [132].

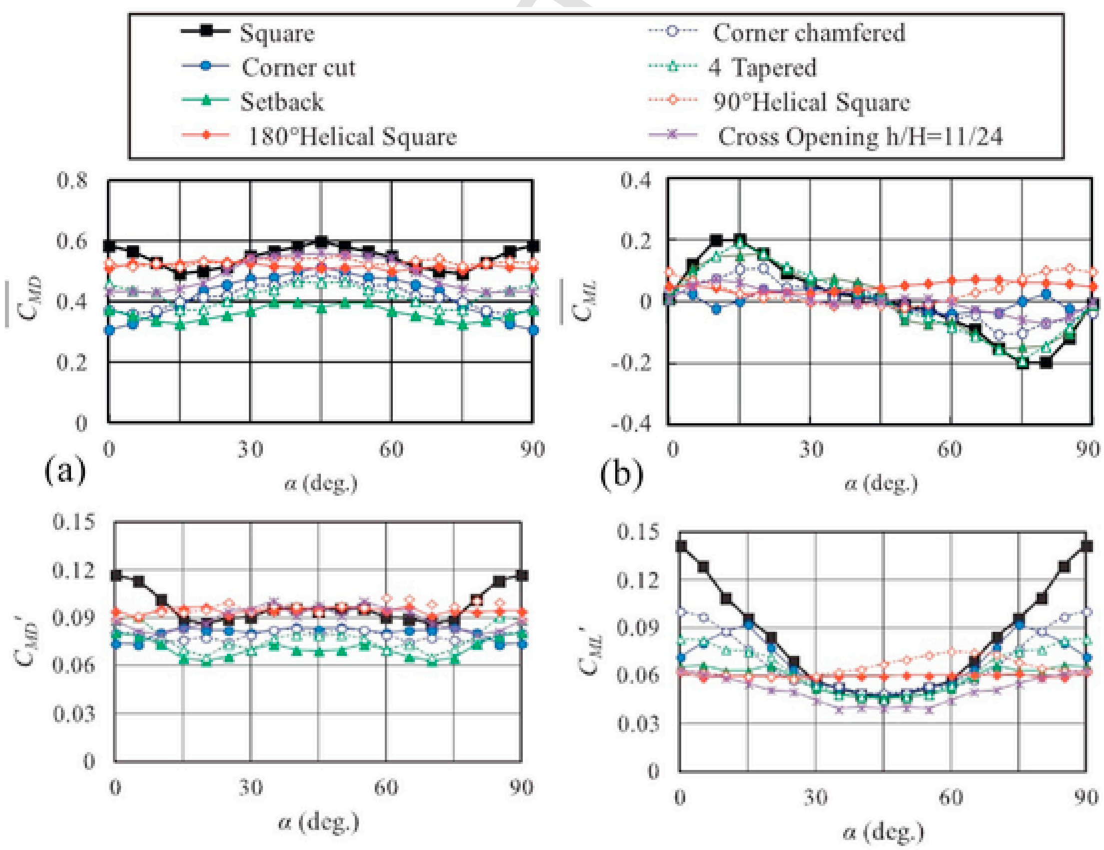

Fig. 22. Mean and fluctuating overturning moment coefficients; (a) along-wind direction, (b) across-wind direction [132].

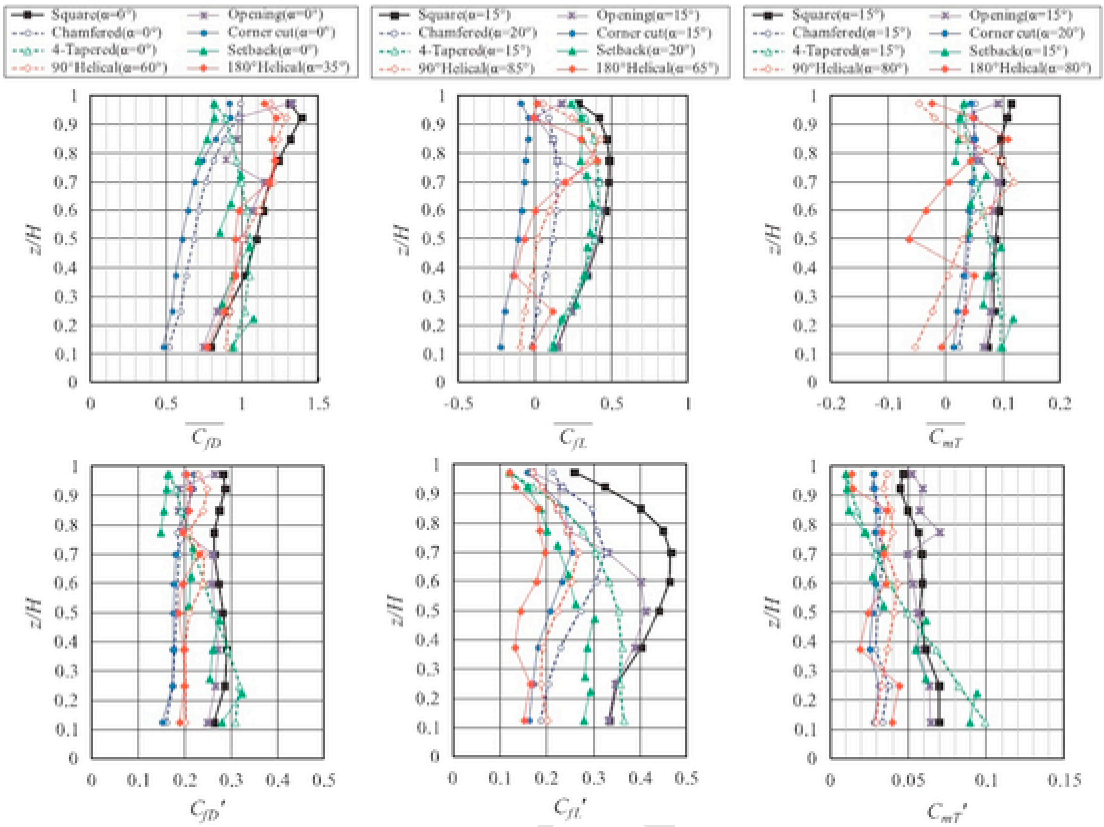

Fig. 23. Vertical profile of mean local wind force coefficients; (a) along-wind, (b) across-wind and (c) torsion [132].

cut, helical with twist angles of 60◦, 180◦, and 360◦. The helical models had the highest impact on the aerodynamic behavior compared with other sections.

The effects of corner modification on flow characteristics of a square cylinder were studied at the Reynolds number ranging from 1.7×10^4 to 2.3×10^5 and incident angle varying from 0° to 45° [143]. Wind tunnel pressure measurements resulted in the identification of the Strouhal number and aerodynamic forces at different incident angles, and it was found that the roundness reduces the critical incident angle, which is corresponding to the flow reattachment. Pressure distribution around a square cylinder with rounded and non-rounded corners is shown in Fig. 27 for two rounded-corner radii (r/b) of 1/15 and 2/15. In another research by Carassale et al. [144], they used the same test rigs to explore the dependency of boundary layer stabilities on the incident angle. They found that rounding corners to modify a cross section has a significant effect on the generation of galloping instability on this structure. Zhengwei et al. [119] used the high-frequency force balanced (HFFB) technique to record the aerodynamic forces of 14 square tall buildings with recessed corners. They investigated the influence of turbulent intensity and corner modification on flow characteristics of tall buildings. The corner recession ratio of 7.5% showed the best performance to mitigate the aerodynamic forces. Kawai [118] explained the impact of corner cut and roundness on aerodynamic instabilities of tall buildings using wind tunnel tests. Experimental results indicated that aerodynamic damping increases for small corner cut and recession modifications while large modification shows more instability at low reduced velocity. Moreover, the rounding cross section was another effective modification that improved the stability of this structure.

Zheng et al. [145] selected a few tall buildings with square, corner-recessed corner, corner-chamfered square, and Y-shaped cross sections to explore the effect of these modifications on wind-induced response using wind tunnel tests. It was found that although all these modifications are effective in reducing the along- and across-wind responses, they might not be helpful in the reduction of torsional response. Li et al. [146] measured the pressure distribution along the building height at various layers to study the influence of three modifications consisting of recessed, chamfered, and rounded models by wind tunnel measurements. The results comparison between original building (square) and modified models with corner cut of 10% showed that the along-wind loads were reduced for corner chamfered at zero incident angle while the across-wind loads were decreased for recessed corners. As a result, they concluded that recessed and chamfered corners are more effective than rounded corners to reduce the wind loads in both directions. Cui and Caracoglia [147] used the random decrement technique to extract the across-wind aerodynamic damping from the acceleration response while modifying the cross section. The experimental tests on buildings with modified sections such as chamfered, slotted, and tapered models showed that these modifications are not always effective for all configurations. Menicovich et al. [148] proposed a new approach called "Fluid-based Aerodynamic Modification (FAM), which manipulates the separating boundary layer instead of reshaping or modifying the geometry of a tall building shape. Wind tunnel results of a rectangular prism indicated a reduction in mean drag and dynamic forces due to the application of the FAM technique. According to the experimental results, low corner cuts including the chamfered ratio of 5–20% and slot ratios of 5–10% as well as low taper ratio of 1% were found to be significant in reducing the aerodynamic loads, but across-wind response increased for substantial modifications including slot ratio of 20% and taper ratio of 3–5%. Although all the aforementioned modifications can be useful to control the wind-induced vibration of a super tall building, it is certainly required to take into account their economic perspectives on construction and material costs. Tse et al. [120] economically evaluated the influence of different aerody-

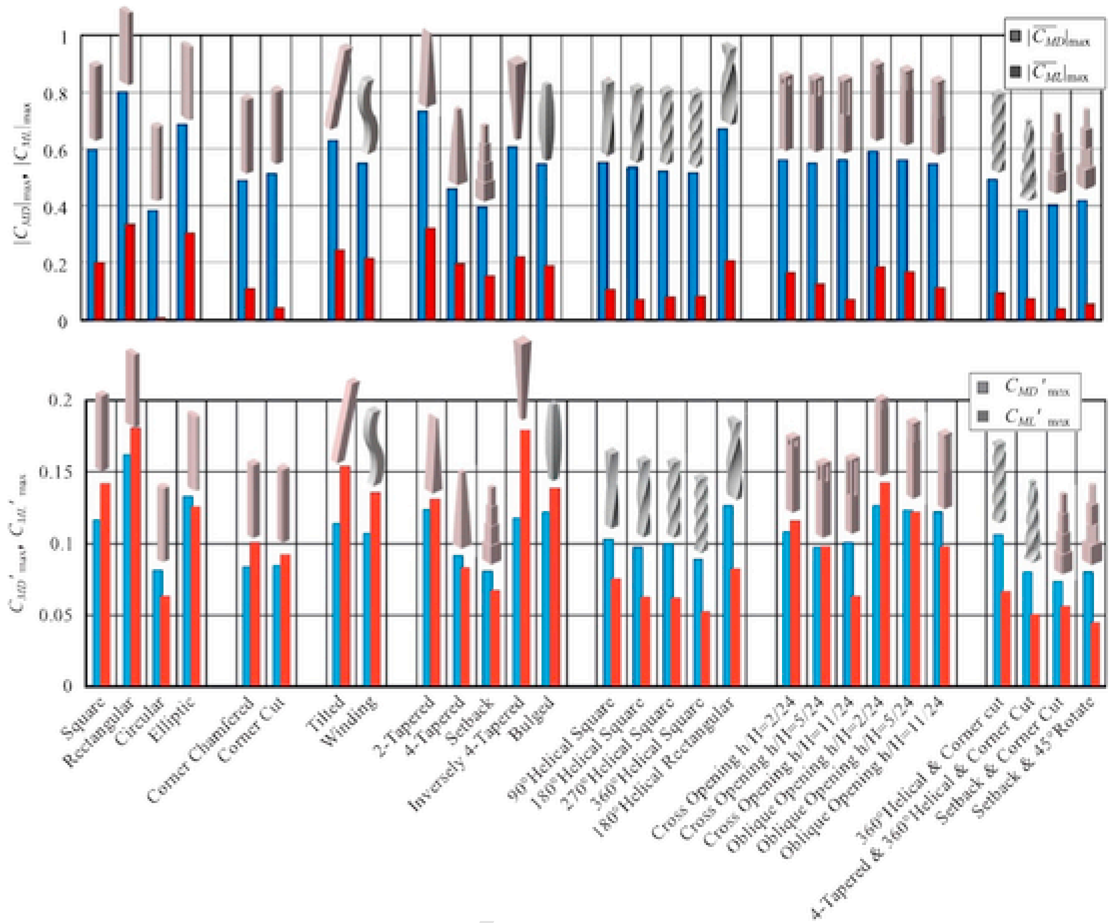

Fig. 24. Comparison of maximum mean overturning moment coefficients [132].

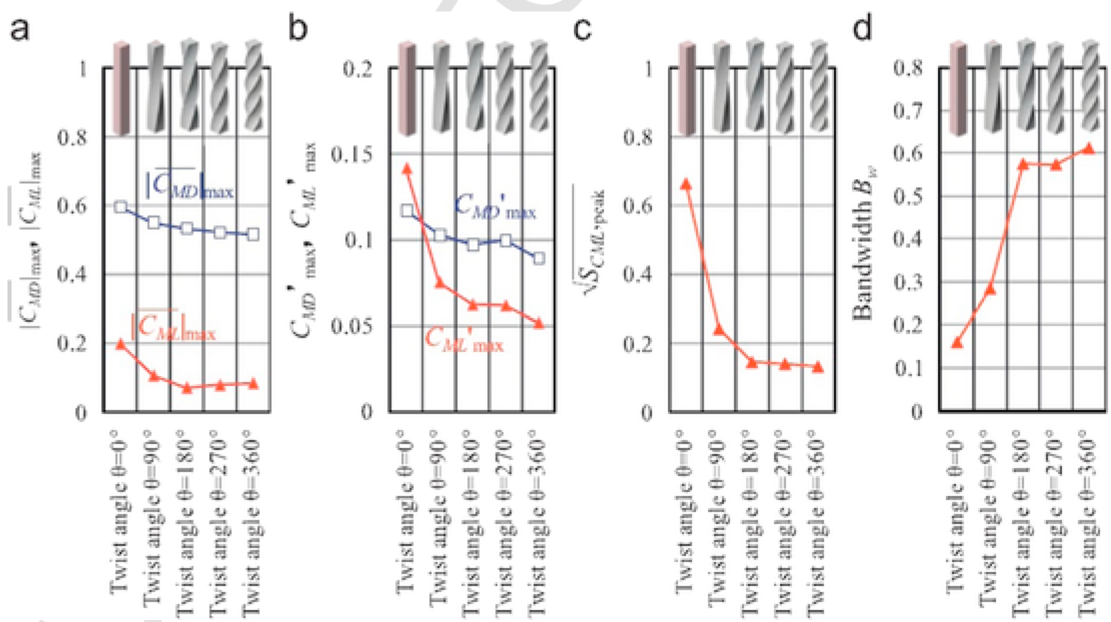

Fig. 25. Effect of twist angle (θ) for the Helical Square Models; (a) maximum mean otm coefficients, (b) maximum fluctuating otm coefficients, (c) peak values of power spectral density, (d) bandwidths of power spectral density [132].

namic modifications on a tall building. In this regard, they performed several wind tunnel experiments on scaled models with modified corners and proposed the empirical equations to demonstrate the dependency of across-wind response on building dimensions and dynamic features. From the experiments on buildings with heights ranging from 240 to 280 m and aspect ratio of 5–5.8, they observed a larger effect for chamfered corners in the reduction of dynamic response in both along- and across-wind directions, but the effectiveness of recessed and cham-

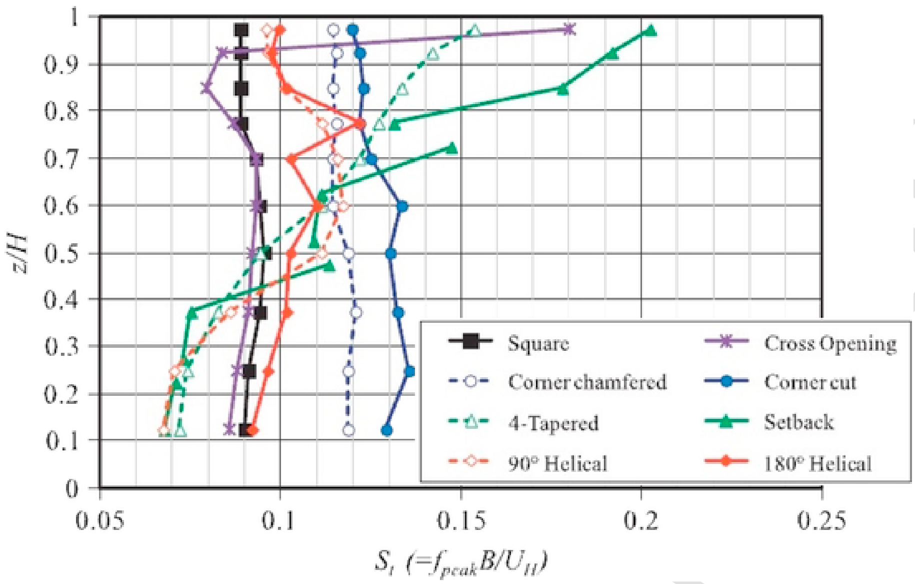

Fig. 26. Vertical profile of Strouhal number along the height of a tall building [132].

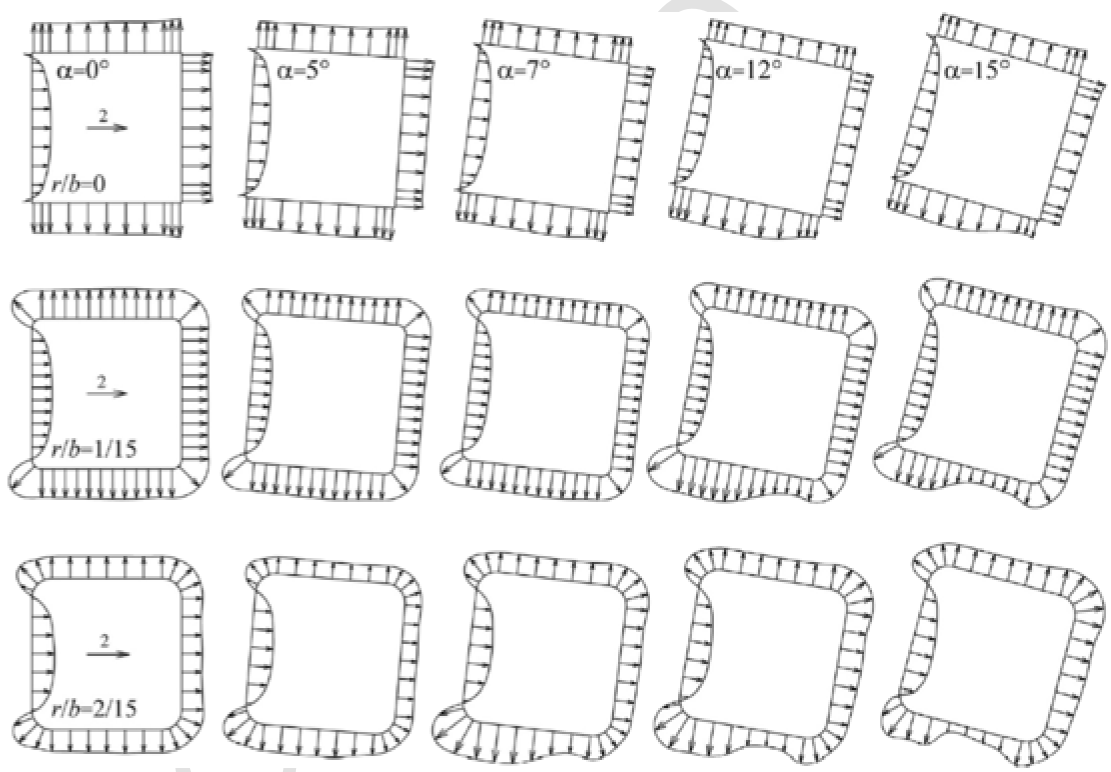

Fig. 27. Distribution of pressure coefficients around a square cylinder with rounded corners at $Re = 2.9 \times 10^4$ [143].

fered corners may become the same while increasing the aspect ratio of building. In general, it was found that the construction cost is less for chamfered and recessed modifications compared to other types.

In recent years, the application of double facades to alleviate the wind load and response of tall buildings has gained considerable attention. Daemei and Eghbali [149] carried out a numerical simulation with Autodesk Flow Design software to study the impact of several modifications on the reduction of wake region behind high-rise buildings. These modifications for triangle and square buildings included rounded, chamfered, and recessed corners. The result indicated that the wake region could be reduced by 30–50% compared to the original building in general. The influence of vertical splitter plates attached to the building's façade was tested by Yang et al. [150] through a series of wind tunnel experiments. The experimental results indicated that vertical plates could effectively change mean and fluctuating pressure, along- and across-wind loads, and base moment. In another wind tunnel testing, Yuan et al. [151] studied the impacts of façade appurtenances attached to a high-rise building on local peak wind pressures. They found that the highest negative peak pressure on the higher leading corner can be mitigated by 42%.

3.1.2. CFD simulation

The accuracy of numerical simulations using Computational Fluid Dynamics (CFD) techniques to model the tall buildings has been evaluated during the past years [152]. They showed that using large eddy simulation (LES) technique is highly recommended to capture the mean and fluctuating components of flow over bluff bodies such as square cylinders [153,154]. Tominaga [155] evaluated the accuracy of Unsteady Reynolds-Averaged Navier–Stokes (URANS) turbulence models including k-ω shear stress transport (SST), standard k-ε, RNG k-ε, and Realizable k-ε by conducting a series of numerical simulations. Numerical simulations of a tall building with these turbulence models demonstrated that only k-ω SST model could accurately model the unsteady flow. Aboshosha et al. [156] developed a new technique to simulate the turbulent intensity profile in CFD modeling and used the large eddy simulation (LES) turbulent model to capture the aerodynamic behavior of flow over a tall building. The comparison of numerical results with experimental data showed the capability of the proposed approach for modeling the wind speed ad turbulent intensity profiles to study this structure. Meng et al. [157] presented the results on a CAARC (Commonwealth Advisory Aeronautical Research Council) standard tall building using numerical simulations to study the effects of turbulence model, wind speed, and grid type on the building pressure coefficient (Cp). Maximum positive Cp was observed around 0.8−0.85H located at the windward side, and the minimum negative Cp emerged at the foreside of the top surface. Turbulence models demonstrated a significant impact on the accuracy, and Realizable k-ε and SST were the most precise turbulence models while the second accurate models were reported as standard k-ε and RNG k-ε. Liu and Niu [154] evaluated the accuracy of a few turbulence models to simulate the flow over a tall building. The turbulence models included RNG k-ε, LES, and detached eddy simulation (DES). They validated the numerical results by wind tunnel data. The results obtained from LES and DDES (Delayed Detached Eddy Simulation) were almost the same while the DDES needed fewer meshes, and hence this model was recommended for modeling the external flow over bluff bodies such as tall buildings.

Zhang et al. [158] studied the wind-induced vibration of a CAARC standard tall building using the CFD technique to capture the unsteady aerodynamic forces and their transfer from the fluid to the solid domain. They validated the numerical results by wind tunnel data and found a good match between them. Figs. 28 and 29 show the streamline and vortex formation over a square tall building along with normalized velocity contour. Fig. 30 demonstrates the three-dimensional flow and Karman-vortex shedding around a CAARC standard tall building using LES modeling. Tamura et al. [113] incorporated the numerical techniques to simulate the tall building with different corner shapes. They observed a significant improvement in the aerodynamics of a tall building by modifying the corner shape. Moreover, they also reported the aerodynamic forces and pressure coefficient around a tall building. Elshaer et al. [159] applied the LES turbulence model and Consistent Discrete Random Flow Generation (CDRFG) to accurately simulate the turbulent intensity profile for numerical modeling of a CAARC standard tall building. They validated the dynamic response and acceleration by comparison with wind tunnel data and observed a good agreement. Chakraborty et al. [160] conducted a series of numerical simulations and experimental tests to evaluate the aerodynamic performance of a tall building with a plus-shaped (+) cross section. The numerical results were also validated by experimental data. Iqbal and Chan [161] used the standard k-ε model to investigate the influence of wind incident angle and passage width on wind flow around cross-shaped (+) tall buildings. Bairagi and Dalui [162] compared the CFD results of two tall buildings with different setbacks using the k-ε turbulence model for simulation. The results indicated that single-side setback has a higher suction (around 96%) on the rooftop compared with both-side setback models while the torsional moment of both-side setback models was nearly 260% more than single-side setback model. Daemei et al. [163] studied the effect of aerodynamic modification on the reduction of the drag coefficient. In this regard, they carried out CFD simulations for tall buildings with taper, twist, setbacks, cham-

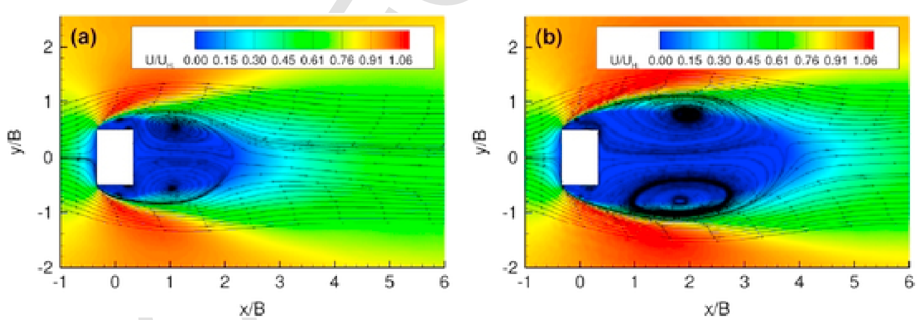

Fig. 28. Mean velocity streamline at height $z/H = 2/3$; (a) turbulent flow, (b) smooth flow [158].

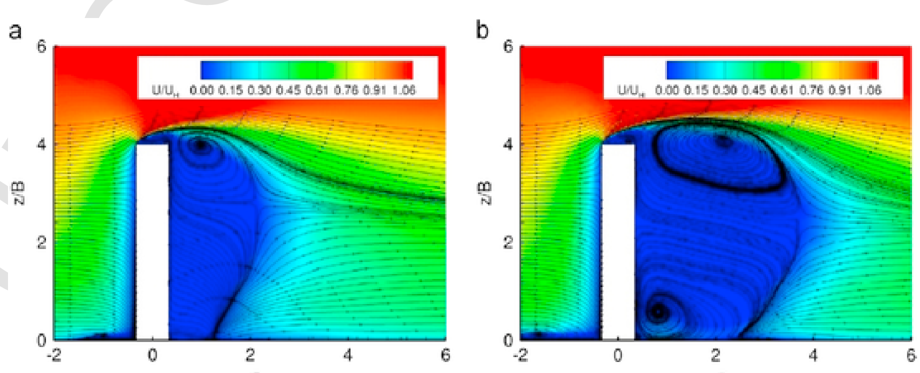

Fig. 29. Mean velocity streamline at middle section; (a) turbulent flow, (b) smooth flow [158].

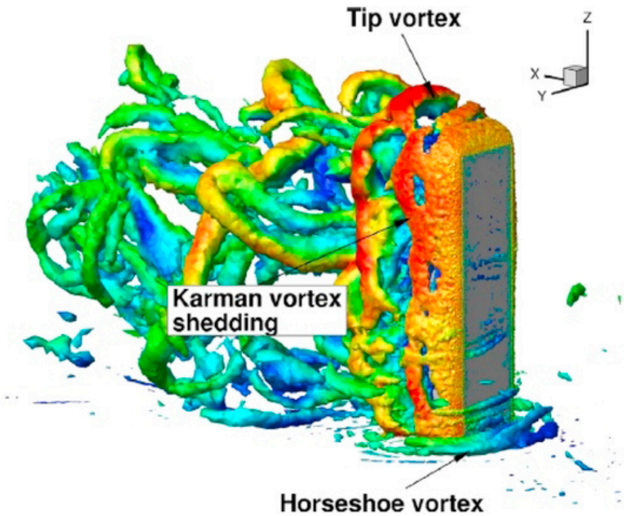

Fig. 30. Large scale turbulent structures around the CAARC building [158].

fer, roundness, and recession. It was found that the drag coefficient of the tall building with rounded corners and tapering was reduced by 66% and 24%, respectively. Druenen et al. [164] carried out a numerical simulation to evaluate the influence canopies, podiums and permeable floors on the aerodynamics of tall buildings.

Table 6 briefly reviews most of the past important numerical and experimental studies over tall buildings to evaluate the aerodynamic performance at uniform or atmospheric boundary conditions.

3.2. Aerodynamic optimization of tall buildings

Wind engineers are required to collaborate with structural engineers and architectures to minimize the aerodynamic and aeroelastic wind loads in both along- and across-wind directions because mean wind speed exponentially increases with height, which generates more complexities in the design procedure. Furthermore, the overall mass of tall buildings needs to be minimized for the sake of earthquake loads, while the contribution of wind-induced loads becomes more after decreasing the mass [170]. Wind loads on tall buildings have been studied in the past, either performing wind tunnel experiments [171,172] or using CFD techniques [173,174]. Past studies showed that the building's outer shape has the most contribution in the generation of aerodynamic drag and lift forces. Although the aerodynamic optimization can minimize the wind-induced loads, other important design parameters such as structural properties and construction cost need to be taken into account while designing a tall building. In this regard, apart from the aerodynamic design, other optimizations and design procedures have been studied in the past for tall buildings such as reliability-base design [175,176], performance-based design [177,178], stiffness optimization [179,180], and structural optimization of a tall building [181,182].

- **Optimum design**

Optimization algorithms have been used to integrate all effective parameters on the aerodynamic and structural design of tall buildings as an optimization problem. In this regard, different well-known optimization algorithms such as genetic algorithm (GA) and artificial neural network (ANN) are developed to aerodynamically optimize the cross section or outer shape of a tall building. Despite the wind tunnel experiments that only a limited number of rigid or aeroelastic models can be tested to compare their aerodynamic performance, optimization algorithms provide the value of most effective design parameters to reduce the aerodynamic and/or aeroelastic loads, material cost, and design process. Fig. 31 simply reveals the general flowchart of an optimization approach in designing a tall building or other structures, which finally results in the determination of optimum design variables after meeting the constraints and objective function(s). As illustrated in Fig. 31, the mesh domain needs to be updated in each iteration due to the change of the design variables, which extends the design process, but mesh morphing techniques that map the mesh to a target topology can accelerate this process. Another important factor influencing the accuracy of a CFD simulation is modeling the turbulent flow to capture the flow separation, vortices, and large eddies. The accuracy of CFD modeling to capture the flow separation, vortices, and large eddies depends basically on the turbulence models, which are employed in the simulation. Turbulence modeling in CFD solvers can be generally classified into three types of Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds-Averaged Navier–Stokes (RANS). Although DNS modeling gives the most accurate numerical results, it is costly and time-consuming due to requiring intense grids (roughly $Re^{9/4}$ cells). On the contrary, LES modeling needs less mesh than DNS and accurately captures the flow characteristics around a bluff body. The last model is RANS that needs coarser grids compared with DNS and LES modeling, but it is not precise in capturing the separation and reattachment over bluff bodies. Detached Eddy Simulation (DES) is a new replacement combining the LES and RANS privileges to conduct simulation with lower mesh and higher accuracy. Since numerical simulation with high fidelity models such as DNS and LES are time-consuming and expensive to run on supercomputers, it is needed to take advantage of optimization algorithms to accelerate the design process.

- **Optimization approach**

To determine the global or local optimum point(s) in an optimization problem, two primary methods that are called “Gradient-based” and “Non-Gradient based” can be utilized as gradient-based methods are generally faster [183–185]. In the recent years, gradient-based methods, also called Evolutionary Algorithms (EA), such as Genetic Algorithm (GA) and Particle Swarm (PA) along with other schemes such as response surface models or surrogate models or metamodels have been applied to optimize the shape and especially cross section of tall buildings. In these algorithms, drag and lift coefficients are usually the objective functions, whereas geometric variables are constraints for a tall building. In surrogate-based optimization, a surface is fitted to random input variables versus output responses, e.g. C_D , C_L', found by CFD simulation, and then surrogate models such as polynomial regression, Kriging or co-Kriging, radial basis functions, neural networks, and support vector regression are applied to determine the optimum points. After this step, new informative sample points are selected for new CFD modeling, and the process of sampling, solving, and resampling repeats until the desired accuracy is achieved. As explained before, CFD simulation with high-fidelity models is not very common due to its high-quality-mesh requirement, but currently, multi-fidelity surrogate modeling such as co-Kriging model has been applied to enhance the accuracy by combining low-fidelity results collected from RANS simulation and a few LES (high fidelity) results [186,187]. Recent studies on aerodynamic optimization of tall buildings indicate promising accomplishments, but new developments are required to simultaneously perform the aerodynamic and structural optimization designs for this structure.

- **Applied methods**

Ding and Kareem [188] applied a surrogate model called “co-Kriging” to optimize the cross-section shape of a tall building by combining the numerical results of both low- and high-fidelity turbulence models (see Fig. 32Figure 33). Random sample points that were chosen

Table 6
Summary of past experimental and numerical studies on tall building aerodynamics.

Reference	B (cm)	D (cm)	H (cm)	Cross section	Shape	$\alpha°$	$\theta°$	Terrain (α)	Tech	Measurements/Results
Aboshosha et al. [156]	30.48	30.48	182.2	SQ	ST	0	0	0.33	CFD	PSD, Co, Dis, Acc
Bairagi and Dalui [162]	20	25	50	SQ	ST, SB	0–180	0	0.133	CFD	C_p
Bandi et al. [127]	7.6 edge	7.6 edge	40	TR, CF, Y, Clover	S, Tw	0–120	0,60,180,360	0.27	WT	C_M C_D, C'_D C_L,C'_L,PSD, *St*
Carassale et al. [143,144]	5–15	5–15	50	SQ, RD	ST	0–45	0	Un	WT	C_D,C_L
Cooper et al. [140]	40	40	250	SQ, CF	ST, TP	0	0	0.2	WT	C_F, PSD, Dis
Cui and Caracoglia [147]	4.7	7.1	28.4	RC	ST	0–90	0	Un	WT	C_M, C_D, C_L, PSD
Dagnew and Bitsuamlak [165]	11.4	7.6	45.7	RC	ST	0	0	0.16	CFD WT	C_p
Dongmei et al. [138]	16.3	16.3	140	SQ	ST	0	0	0.22	WT	C_P, PSD
Elshaer et al. [159]	11.4	7.6	45.7	RC	ST	0, 90	0	0.17	CFD WT	VF, C_p, M, PSD
Gu and Quan [133]	67–300	67–100	180	SQ, RC, CF, CN	ST	0	0	Cat A, B, C, D (China)	WT	PSD, ζ_a, Dis,
Gu et al. [166]	7.5	7.5	60	SQ, CF, ST	ST, TP	0	0	0.22	WT	ζ_a
Hayashida and Iwasa [114]	8–12	8–12	60	SQ, TR, CR, RD, RS, Y	ST	0, 45	0	0.25	WT	C_D, PSD, Dis
Hu et al. [138]	30	20	120	RC	ST	0	0	0.15	WT	PSD, Dis, CCo
Huang et al. [167]	11.25	7.5	45	RC	ST	0	0	0.15	WT CFD	C_p, C'_P, TKE, VF
Kawai [118]	5	5	50	SQ, CR, CF, RS, RD,	ST	0	0	0.2	WT	PSD, Dis
Kim and Kanda [131]	10	10	40	SQ	ST, TP, SB	0–45	0	0.13, 0.24	WT	C_p C_D, C'_D C_L C'_L, PSD, Co, *St*
Kim and Kanda [128]	10	10	40	SQ	ST, TP, SB	0, 90	0	0.13	WT	C_P, Co, PSD
Kim and You [123]	4,6,8,10	4,6,8,10	40	SQ	ST, TP	0–60	0	0.15, 0.30	WT	PSD, Dis, C_F
Kim at el [138].	5	5	40	SQ, CF, CC	ST, TP, SB, OP, MS, TW	0–90	0,90,180,360	0.27	WT	S, M, F
Kim et al. [129]	10	10	40	SQ	ST, TP, SB	0	0	0.13	WT	PSD, Acc, Co
Kim et al. [124]	54,64,72,80	54,64,72,80	32	SQ	St, TP	0	0	0.15	WT	Dis
Kim et l [136].	5	5	40	TR, SQ, PTG, HXG, OCTG, DDTG, CR	S, TW	0–180	180	0.27	WT	M, PSD, Dis
Kwok and Bailey [116]	6	6	54	SQ, ST, FN, VNT	ST	0	0	0.15	WT	PSD, Dis
Li et al. [146]	10	10	80	SQ, RS, CF, RD	ST	0–90	0	0.22	WT	C_p, C_D, C'_L, PSD, M, Co
Liu and Niu [154]	D	B	2B	SQ	ST	0	0	0.27	CFD	VF, PSD
Meng et al. [157]	45.72 m	30.48 m	182.8 m	RC	ST	0	0	0.27	CFD	C_P
Menicovich et al. [148]	7	3.5	52.5	RC	ST	0–90	0	0.11,0.15, 0.25	WT	C_F, *St*
Miyashita et al. [115]	13	13	79	SQ, TO, CF, RS	ST, OP	0–45	0	0.15	WT	C_F, PSD
Tamura and Miyagi [117]	50	50	30	SQ, CF, RD	ST	−5–+50	0	Un	WT	C_D, C_L, PSD, *St*
Tanaka et al. [132]	5	5	40	SQ, RC, CR, EP, CF, CC	ST, TP, OP, TW, SB	0–90	0,180,270,360	0.27	WT	C_P, C_D, C_L, M, PSD, *St*
Tominaga [155]	B	B	2B	SQ	ST	0	0	–	CFD	PSD, TKE
Yu et al. [168]	15	10	60	RC	ST	0	0	0.22	CFD, WT	C_p, C'_P, PSD, M, Dis

Table 6 (*Continued*)

Reference	B (cm)	D (cm)	H (cm)	Cross section	Shape	$\alpha°$	$\theta°$	Terrain (α)	Tech	Measurements/Results
Zhang et al. [158]	11.4	7.6	45.7	RC	ST	0	0	0.28	CFD	C_P, C_F, Dis, Co
Zheng and Zhang [152]	16.2	16.2	60	SQ	ST	0	0	0.22	CFD	C_p, C_D, C_M, TKE
Zheng et al. [145]	11.8	11.8	60	SQ, Y, RS, CF	ST	0–60	0	0.22	WT	PSD, Dis
Zhengwei et al. [119]	5	5	60	SQ	ST	0–45	0	Cat B, D	WT	C_M
Zhou et al. [169]	5.1–15.24	5.1–15.24	40.6–53.3	SQ, RC, TR, RM	ST	0	0	0.16,0.35	WT	PSD

Keynotes: Tech: Technique; $\alpha°$: Incident/attack angle; $\theta°$: Twist angle; Co: Coherence coefficient, M: Moment, Dis: Displacement, Acc: Acceleration; VF: Velocity field; PSD: Power spectral density; S: Stress; F: Force; TKE: Turbulent kinetic energy; ζ_a: Aerodynamic damping; CCo: Cross correlation; Un: Uniform flow; CFD: Computational Fluid Dynamics; WT: Wind tunnel test; RC: Rectangular; TR: Triangle; RM: Rhombus; PTG: Pentagon; Hexagon: HXG; OCTG: Octagon; DDTG: Dodecagon; EP: Ellipse; ST: Straight; SB: Setback; CF: Chamfered corners; ST: Slotted corners; RD: Rounded corners; CR: Circle; RS: Recessed corners; FN: Fins; VNT: Vented corners; CN: Concave corner; MS: Mulita-section shape; CC: Corner cut; OP: Openings; TO: Through openings; PL: Plus shape.

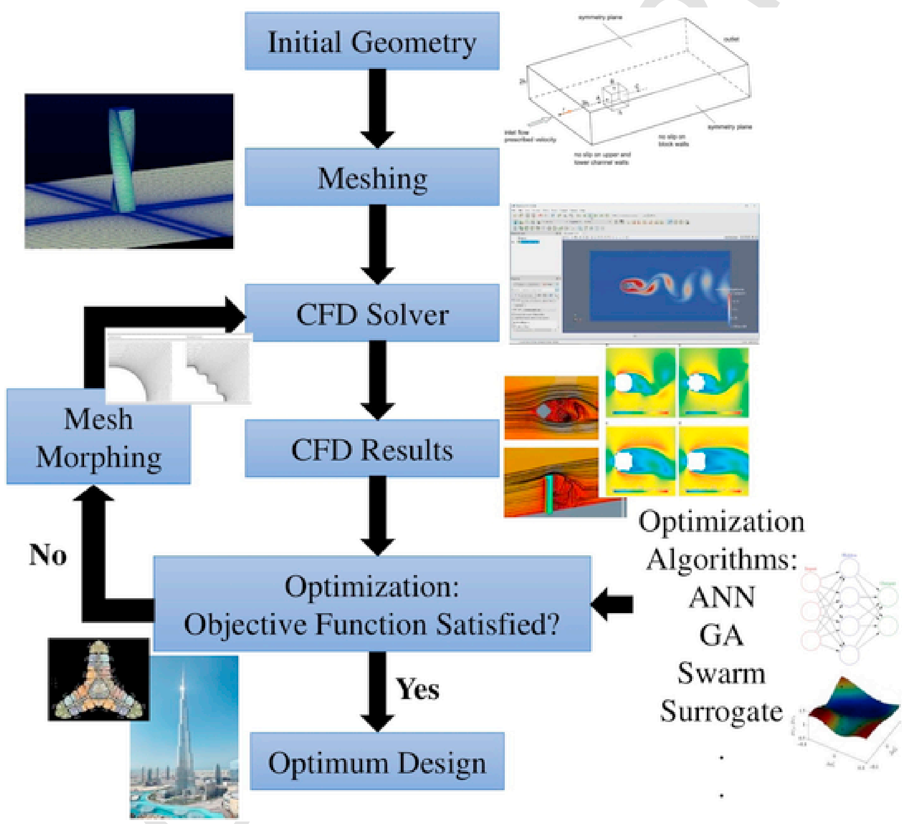

Fig. 31. Flowchart of optimization algorithm using CFD modeling.

to run the first simulations are shown in Fig. 32. They used the LES results to increase the accuracy of minimizing the drag coefficient (C_D) and fluctuation component of the lift coefficient (C'_L). They proved that the proposed approach was very efficient to carry out aerodynamic-shape optimization by using multi-fidelity models. Bernardini et al. [189] performed a design optimization on the cross section of a tall building by CFD simulation along with the ordinary Kriging surrogate model to determine the optimal design variables while minimizing the lift and drag coefficients. The Pareto front framework was also employed to choose the optimum points. According to the promising results, they recommended the surrogate-based multiobjective optimization framework to optimize the building shape or cross section. Elshaer et al. [190] introduced an aerodynamic optimization procedure (AOP) to design the tall buildings using CFD modeling and Artificial Neural Network (ANN) while minimizing the along-wind base moment. They employed the LES turbulence model for the numerical simulation and showed that the corner modification and twisting can aerodynamically optimize this structure by reducing the wind loads. Elshaer et al. [191,192] developed a procedure to design the corners of a tall building using CFD modeling (LES) and optimize with the Genetic Algorithm (GA). They showed the excellent capability of the proposed method to minimize the drag load. Elshaer et al. [121] proposed an optimization framework to design the corners while minimizing the drag and lift forces. They coupled LES modeling and artificial neural network (ANN) as an optimization scheme and observed a huge reduction of wind response (>30%) in both directions. Wei et al. [193] introduced a framework for a structured mesh with moving boundary conditions us-

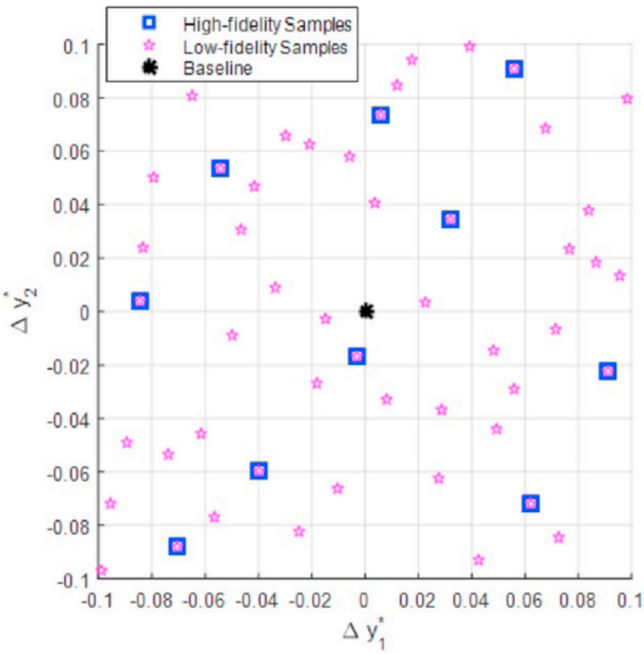

Fig. 32. Multi-fidelity sampling plan to run the CFD modeling [188].

ing morphing techniques to accelerate the simulation process for the optimization of tall buildings. They showed the high efficiency of this technique for modeling the bridge deck and tall building. Xie [194] proposed an approach while performing limited wind tunnel data to aerodynamically optimize a tall building and study the influence of tapering, twisting, and setbacks. He applied the proposed approach to past experimental data presented by Tanaka et al. [132,195] to validate the results for tapering and twisting modifications. The results showed that although stepping and tapering can decrease the across-wind response, they may increase the acceleration in low reduced velocity, which affects occupant comfort [196] (see Fig. 33).

In this section, the necessity of optimizing the tall buildings' shape was elucidated, and a brief review of the past applied optimization algorithms in this area was delivered. Overall, it can be concluded that designing a tall building with optimized shape may never accomplish unless an excellent collaboration between wind and structural engineers happens through the integration of structural and CFD codes to find the optimum design while meeting all criteria and standards. To this end, it is essential to employ the high- and low-fidelity CFD models along with advanced optimization algorithms to capture all nonlinearities in the system.

- **Performance-based design**

This approach, which is the integration of various approaches and criteria, has been recently gained more attention to optimize the tall building shape considering broad effective parameters. Bernardini et al. [197] proposed a framework for occupant comfort of the tall buildings using the performance-based design (PBD) that was developed based on probabilistic wind events and various uncertainties impacting structural responses such as wind speed and modal characteristic. The aim of this method was to introduce a design procedure that provides enough information for designers to consider the effective parameters such as dynamic response on the material selection or other objective functions. Bobby et al. [198] developed a design framework to optimize the tall building while considering the conceptual design, structural system, and detailed design. In fact, this framework presented as a bridge between the aerodynamic and structural aspects of tall-building design procedure through a CFD modeling (see Fig. 34). They employed performance-based topology optimization and used morphing techniques to automatically update the mesh. The obtained results for a case study showed the accuracy and efficiency of the proposed framework. Bobby et al. [199] presented an optimization scheme to design the shape of a tall building by minimizing the building volume or material costs and reducing the wind-induced loads in either along- or across-wind direction. They used the performance-based topology optimization for three cases to evaluate the accuracy of the proposed approach, and the results showed its high capability in optimizing a tall building. Spence and Kareem [200] introduced a performance-based design optimization while decoupling the nested probabilistic analysis from optimization algorithms and also applied Monte Carlo simulation for uncertainty propagation. Lee et al. [201] established a framework to conduct the shape and topology optimizations using a reliability-based design algorithm. They employed the OpenFOAM as an open-source solver for CFD modeling and proved the good capability of this approach for the determination of optimum design variables. Chan and Chui [202] integrated the wind tunnel data and automatic least-cost design optimization to define the design variables of a tall building with the least construction cost. They developed an Optimality Criteria (OC) method to minimize the structural cost and also verified the results of this method by comparison with wind tunnel data. Li and Li [203] studied the wind-induced response of a tall building with irregular shape using op-

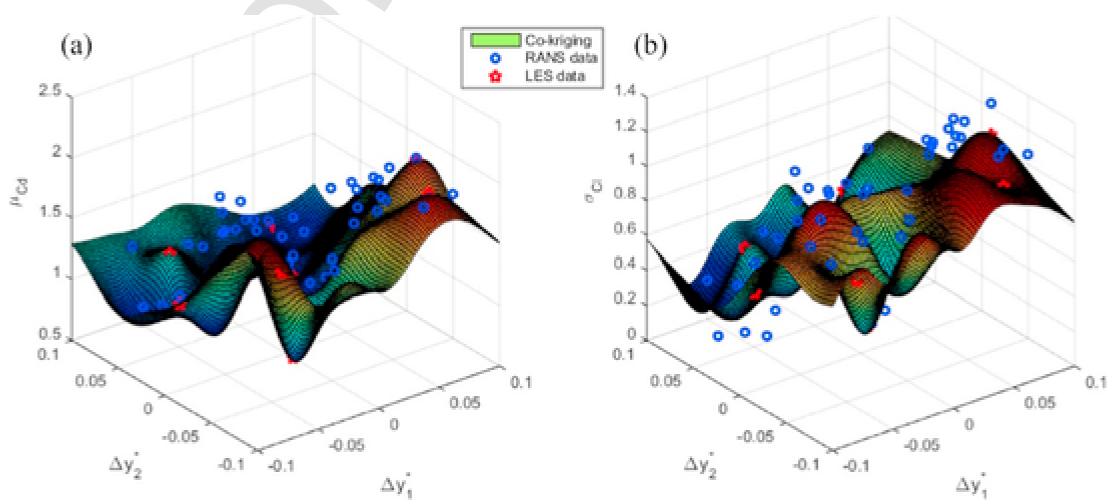

Fig. 33. Multi-fidelity surrogate models for two aerodynamic objectives; (a) mean drag coefficient, (b) standard deviation of lift coefficient [188].

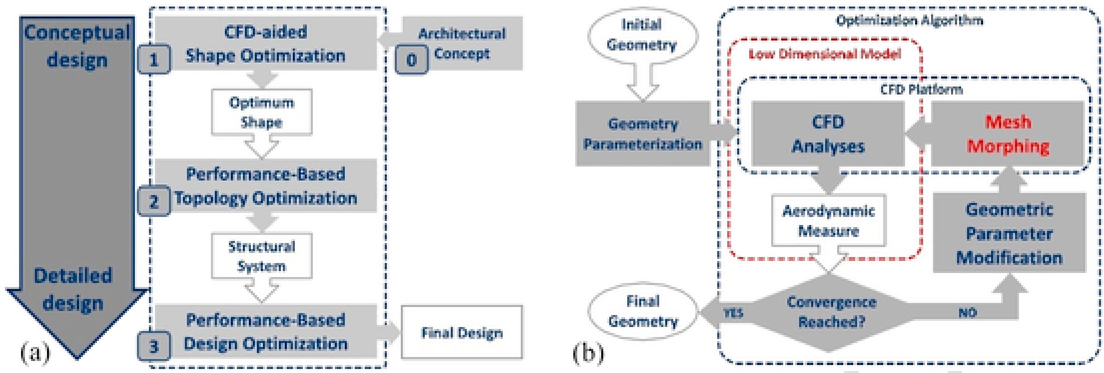

Fig. 34. Schematic view of proposed optimization applying performance-based design approach; (a) design framework, (b) shape optimization framework [198].

timization algorithms. In this regard, they integrated the OC method and a recursive algorithm to determine the optimal values for design parameters. They validated their scheme by wind tunnel data, which was perfumed on an L-shaped tall building. The results indicated that the overall building weight and equivalent static wind load were reduced by 18.1% and 9.03%, respectively.

Laura et al. [204,205] used the performance-based design (PBD) to improve the design of the damping system exposed to wind loads acting on tall buildings. They applied the effect of occupant discomfort caused by wind-induced vibration of building, and they concluded that the PBD is a rational and economical method to design more effective damping system for tall buildings. In another study by Laura et al. [206,207], the application of the Kriging surrogate and adaptive wavelet network (AWN) for designing high-performance control systems of tall buildings excited by wind were studied through modeling a 39-story building equipped with semi-active friction. The results indicated that although the accuracy of the Kriging model is higher, the adaptive wavelet network is a faster method with acceptable accuracy. Studying the life-cycle cost evaluation for the high-performance control system was conducted by Laura et al. [208] to investigate the effects of uncertainty involving in the controlled system, and they compared the results with the uncontrolled system exposed to undesired excitation. Deng et al. [209] proposed a new framework for the performance-based wind-resistant design of a CAARC building while considering the joint probability distribution of wind speed and direction obtained from long-term wind measurements of local meteorological stations. The optimization-constraint conditions were the failure probabilities in terms of the maximum displacement, interstory drift, and wind-induced acceleration responses at different design levels. They found this framework efficient in optimizing the building designing while minimizing the wind impact. Cui et al. [210] presented a novel framework for life-cycle downtime analysis of tall buildings. In their approach, they combined wind-induced inconveniences: occupants' discomfort, failure of key equipment, and nonstructural damages on the façade. The results of this study would help determine the optimal building orientation since the wind direction is very effective in designing tall buildings.

4. Conclusions

This paper mainly focuses on reviewing the mitigation systems used in the past for wind-induced vibration of high-rise buildings. Furthermore, aerodynamic modification of tall buildings to alleviate the wind loads is individually discussed along with reviewing past applied optimization algorithms to find the best design. Over the past decades, extensive research has been conducted on the vibration mitigation of tall buildings exposed to the earthquake. As a result, many damping systems, including passive, active, and semi-active, have been invented and evaluated through experimental and numerical techniques, and their high performance has led to their implementation for the actual buildings. Among these damping systems, although active control devices may destabilize the system due to the change in parameters, they have shown more effectiveness for their versatility to damp out the vibration energy in high-rise buildings compared to the passive systems. On the other hand, providing large-needed force to dissipate the energy requires an active system to consume high energy. To conquer this drawback, semi-active systems can be excellent candidates to take advantage of both active and passive systems. Recent tall building projects indicate that the number of buildings with a height greater than 200 m is exponentially growing all around the world. Construction of these gigantic buildings makes the wind-induced load a key factor for the structural design. Therefore, the application and efficiency of conventional dampers need to be reassessed for along- and across-wind loads to ensure the serviceability of future skyscrapers. Furthermore, new damping systems, which could be the combination of existing dampers such as combined tuned damper (CTD), are required to be evaluated under extreme wind loads. To this end, sufficient information about self-excited, vortex shedding, and buffeting forces can help to accurately assess the performance of these dampers.

Studies prove that a small change in the building shape may lead to an incredible improvement in reducing the vortex-shedding strength and aeroelastic loads. The designing phase of a high-rise building usually encounters several restrictions such as construction area, economic target, material, and engineering limitations. However, major or minor modifications to building shape can happen if the designing engineers have an efficient collaboration to come up with the best design. The most popular shape modifications are but not limited to changing the corners through roundness, chamfer, and recession or manipulating the overall building shape through tapering, twisting, opening, and setback. A 30–60% wind-induced load reduction might be achieved with minor medication through narrowing the wake area behind the building. This is while the major modification mainly interrupts the correlation of vortex shedding and changes the shedding frequency along the height, which results in load and response reduction.

The new generation of tall buildings has a fascinating shape and incredible high height. These two factors bring more complexity and challenges for wind engineers. The existing challenges, solutions, and future studies on wind-response mitigation of tall buildings are summarized below. Developing new research projects while considering these points provide sufficient knowledge and information for the construction of safer and taller buildings.

- According to the building standards, the wind-induced accelerations and drifts should be lower than a specific value for human comfort and integrity of non-structural components. Large acceleration in super-tall buildings, which may cause motion sickness, disruption, and discomfort feeling, need to be fully investigated for future buildings to come up with the best damping system.

- Although damping systems have been implemented in high-rise buildings for many years, new buildings with a height greater than 250–300 m require specific attention because wind loads play a significant role at these slender structures compared to earthquake load. The applications of new damping systems such as shape memory alloy and particle damper need to be studied.
- Full-scale measurement on tall buildings with a focus on wind effects has not been sufficiently performed because of its difficulty and expenses. However, it is essential to invest in this area to collect more realistic data for the verification of numerical and experimental results. The obtained results from new studies will be more reliable after this validation with field data.
- Existing building codes and standards have been successfully used for buildings with height less than 300 m, but increasing the height requires revising the available criteria. This improvement can be achieved by conducting more realistic studies on building with larger scale and aspect ratios under atmospheric boundary layer (ABL) wind profile with the help of either wind tunnel test or numerical analysis.
- It is crucial to design new instruments for velocity, force, and pressure measurement to provide more accurate data for non-synoptic wind profiles in thunderstorms, tornados, and downbursts. Continuous data collecting from sensors installed on the building and weather forecast models can lead to the prediction of wind response. This monitoring system helps to control the vibration through active dampers or other smart mitigation systems like smart double facades. Besides, it is a good idea to apply the artificial intelligence algorithms to the existing structural health monitoring techniques in order to predict the wind response and load of tall buildings through weather forecasting.
- It is promising that new advances in the CFD modeling and machine-learning-based algorithms may accelerate and enhance the design procedure for complex tall buildings by considering construction and structure design criteria along with economic aspects and building performance. It should be noted the recent powerful supercomputers enable us to implement the high-fidelity CFD models to overcome the existing challenges in wind tunnel testing. This advancement can lead to constructing new tall buildings with minimized wind-induced vibration.
- The impact of aerodynamic modifications cannot be disregarded, but these modifications may sometimes have the opposite effect depending on the local environmental conditions. Therefore, these modifications should be deployed considering all the effective parameters, i.e., wind flow characteristics, surrounding environment of the building, geometrical and economic constraints. Moreover, it is essential in future studies to explore the influence of combined aerodynamic modifications (major and minor) on building response and provide a roadmap for the design team.
- Recent studies indicate that double façades can mitigate the wind-induced response significantly by changing the pressure distribution around the building with porous media. Since the direction of mean wind speed changed around the buildings, smart double façades than can change their configurations based on the wind condition can be an excellent solution to control the wind load for existing or new tall buildings.
- Efficient collaboration is required between wind, architectural, and structural engineers to find the optimum design for a building. To this end, developing an engineering software with the capability of designing building and running the structural and aerodynamic codes at the same time can be a time-saving solution to upgrade the current design procedure.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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