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Review of approaches, opportunities, and future directions for improving aerodynamics of tall buildings with smart facades

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A R T I C L E I N F O

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A B S T R A C T

The demand for tall buildings has increased over the past decades for cultural, financial, and technological reasons. Such slender structures are more flexible and vulnerable to wind-induced vibrations. Additionally, wind speed exponentially increases with height, resulting in larger wind loading on higher levels and complex turbulent regimes. Such effects call for more innovative approaches to enhance the resilience of tall buildings while accounting for the sustainability implications. Current methodologies to control the vibrations using auxiliary dampers are typically limited in their applicable bandwidth. The aerodynamic modifications are specific to a particular wind direction and characteristics and cannot adapt to the changing climate or that of flow regimes due to the new construction in the proximity of the target building. There have been major advances in using secondary façades to achieve sustainability through ventilation and energy-saving applications around the world. These advances have resulted in the development of adaptive facades for architectural and energy applications. This review paper discusses the available approaches and potential opportunities to utilize the existing adaptive façade system capabilities (for energy applications) to alter building aerodynamics. For this purpose, the paper concisely discusses aerodynamic modification, surface roughness effects, available bio-inspired approaches, and potential morphing material capabilities to provide valuable insights into understanding the flow-control mechanism of such systems, potentially leading to innovative designs of façade systems. Opportunities have been identified to combine this concept with smart technologies to develop smart façades with the aerodynamic performance that leads to mitigating wind-induced vibration in tall buildings. The review of existing research on this topic opens up opportunities for enhancing the use of facades as active, dynamic, and smart systems that not only enhance the performance of the tall buildings under wind-induced vibrations but also can result in long term energy saving, leading to more resilient and sustainable communities.

1. Introduction

Due to continued urbanization and technological advancements, the number of tall buildings worldwide has been exponentially increasing. These structures are exposed to complex loading phenomena caused by urban aerodynamics induced by surrounding the cluster of tall buildings (Micheli, Alipour, Laflamme, & Sarkar, 2019). The response of these structures to wind loads is an important consideration in their design (Hou & Jafari, 2020). The extensive literature included in this review lends insight into the effects of aerodynamic adjustment on wind load reduction exerted on tall buildings (Bibri & Krogstie, 2017; Sandanayake, Lokuge, Zhang, Setunge, & Thushar, 2018). With increased knowledge on this subject, tall buildings can be designed to better withstand wind loads leading to more resilient and sustainable cities (Micheli, Alipour, & Laflamme, 2020a, 2020b; Micheli, Alipour, & Laflamme, 2019 and 2021). Additionally, this knowledge can benefit from and enhance the opportunities to optimize natural ventilation and improve the sustainability of tall buildings (Abdullah & Wang, 2012; Li, Zheng, Liu, Qi, & Liu, 2016).

The ever-increasing number of tall structures boosts the need for designs that can resist wind-induced loads integrated with other natural hazards (Luo, Yin, Peng, Xu, & Zhang, 2019; Zhong et al., 2019). Tall buildings must be designed considering all significant factors, including wind loads, to reach socially resilient and environmentally sustainable cities. Thus, it is essential to utilize past and current techniques to mitigate the wind effects through innovative approaches such as smart façades. The exponential increase of wind speed with height, combined with increases in building aspect ratios, makes them more flexible and

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consequently more vulnerable to wind-induced loads. As a result, these flexible structures are prone to larger displacement and acceleration that results in potential building-cladding damage under wind events (Micheli, Cao, Laflamme, & Alipour, 2020; Micheli, Hong, Laflamme, & Alipour, 2020; Samali, Azad, & Ngo, 2014; Vega & Konz, 2009; Williams & Kareem, 2003) or occupant discomfort due to motion sickness or sopite syndrome (Lamb & Kwok, 2017; Micheli, Cao et al., 2020; Micheli, Hong et al., 2020). Buildings act as bluff bodies, so associated aerodynamics with increasing height and wind speed increases the complexity and exposes them to various phenomena, including but not limited to vortex shedding, turbulence, and flow separation, all of which highlight the necessity of using vibration-mitigation strategies (Micheli, Alipour, & Laflamme, 2018; Micheli, Alipour, Laflamme et al., 2019). The existing motion-reducing approaches can be generally divided into three categories: aerodynamic modification, structural design modification, and addition of auxiliary dampers (Jafari & Alipour, 2020). Apart from these common load-induced mitigation approaches, the recent studies (Blanco, Buruaga, Cuadrado, & Zapico, 2019; Eom, Kang, & Choi, 2019; Urbán et al., 2016) using either wind tunnel testing or computational fluid dynamics (CFD) technique have shown the positive impact of different types of façades such as double-skin facades, perforated facades, or even balconies that add roughness to the surface of building on its aerodynamics. To this end, this study discusses the recent accomplishments and advances in aerodynamic shape modifications, especially with a focus on those associated with facades to highlight the potential opportunities for mitigation of wind-induced loads and vibrations using the building envelope. Changing the applicability of the building facade to modify tall building aerodynamics requires a deep understanding of already-proven aerodynamic design procedures for bare-tall buildings. For example, the influence of corner-cut and setbacks that have been used for the shape modification of buildings can inspire the design of the exterior façade in order to alleviate the effects of sharp corners, flow separations, and vortex-shedding formation. For this purpose, aerodynamic shape modification and surface roughness and their effects on building aerodynamics are briefly reviewed here to provide a better overview of the efficient design of next-generation facades.

Existing aerodynamic shape modifications are divided into two main categories: major modifications that change the overall building shape, including but not limited to tilting, tapering, setback, helical, and composite; and minor changes dealing with cross-section that include corner-cut, rounded corners, recessed corners, and chamfered corners. Apart from these categories, modifications of the buildings' surface roughness significantly influence wind-induced pressure and load. Consequently, these modifications can substantially alter the buffeting, self-excited, and vortex-shedding forces that produce along- and across-wind excitations (Fu, 2018; Irwin, 2008).

Double skin façade (DSF) use a second envelope separated by an air corridor from the interior building envelope (see Fig. 1) to assist with the building ventilation and energy saving. Double-skin façades have received extensive acceptance from the architectural engineering and building design community and have been implemented in many instances across the world (Li, Zhong, & Zhai, 2020; Park, Augenbroe, Sadegh, Thitisawat, & Messadi, 2004). Over the past decades, DSFs have become a staple architectural component of tall buildings, with the first passive double-skin façades constructed in the early 1900s to increase daylighting (Pollard, 2009). DSFs offer many beneficial features, including but not limited to preheating of ventilation air through sunlight (Pomaranzi, Daniotti, Schito, Rosa, & Zasso, 2020), night cooling, thermal and sound insulation, heat transfer (Darkwa, Li, & Chow, 2014), energy-saving (Yang, Yuan, Qian, Zhuang, & Yao, 2018), natural ventilation (Barbosa & Ip, 2014; Wang, Chen, & Li, 2020), and solar or wind energy harvesting (Hassanli, 2019; Hassanli, Hu, Kwok, & Fletcher, 2017; Hassanli, Hu, Fletcher, & Kwok, 2018; Hassanli, Kwok, & Zhao, 2018). A new innovative take on DSFs is the kinetic façades or adaptive facades that can change dynamically based on factors such as sun location or seasons compared to the preliminary versions. The kinetic DSFs have motorized windows, openings, levers, or porous plates.

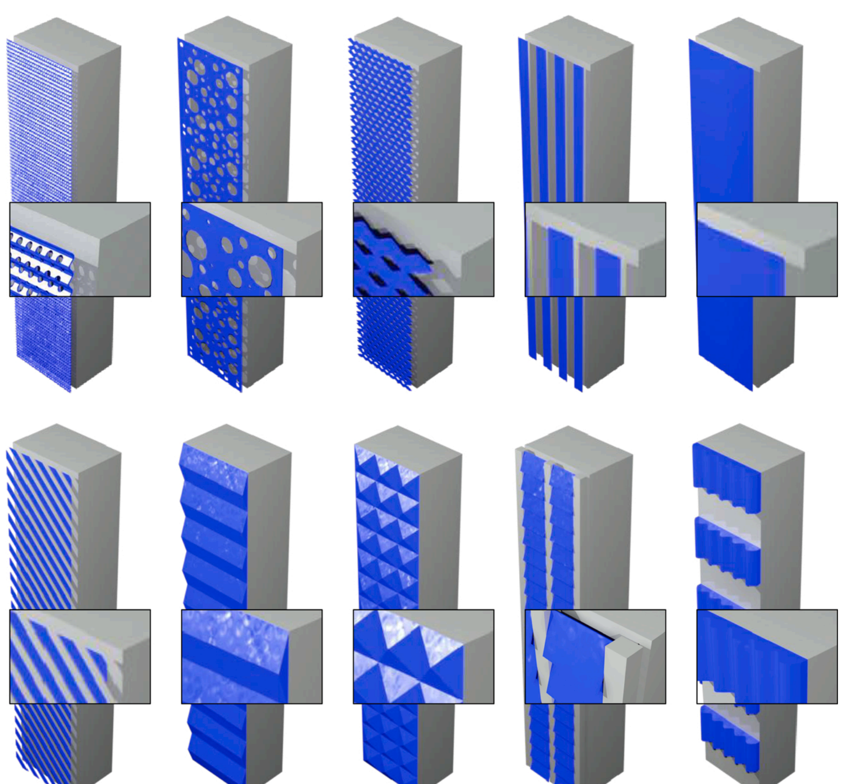


Fig. 1. Schematic view of typical double-skin façades installed on tall buildings.

They can integrate all the applications associated with static DSFs while allowing adaptation to climate factors using an integrated control system and structural health monitoring. Considering that the façade geometry in DSFs can provide an opportunity to create surface roughness and pressure change, there is a potential to enhance their application by taking advantage of aerodynamic modifications to minimize wind-induced excitation in tall buildings.

This paper reviews several past studies to provide sufficient information on existing aerodynamic modification and roughness altering approaches, advancements regarding sustainable aspects of DSFs, and seeks opportunities to integrate the sustainability and resilience enhancing components of the two approaches towards sustainable and resilient buildings and eventually societies. This paper is organized as follows: The building shape and wind direction effects on tall buildings' aerodynamics are discussed in Section 2. Section 3 reviews the aerodynamic shape modification and explains their impact on wind-induced loading on tall buildings. The effect of surface roughness is studied in Section 4 by introducing passive and active façade systems. Section 5 reviews aerodynamic applications of DSFs to reduce wind-induced load and responses. Section 6 briefly describes the architectural application of adaptive façades. The last section expresses the concluding remarks and a description of future research opportunities.

2. Building shape and wind direction effects

Two major factors influencing the aerodynamics of each tall building are shape and wind direction. In this section, these two parameters are briefly discussed through reviewing past relative papers. The studies reviewed here are intended to provide a better intuition to take into account those parameters affecting the wind-induced loads on tall buildings. To explore the shape effects, polygon buildings have been tested with different side numbers ranging from the square (four sides) to circular (infinite sides) shapes to closely examine the cross-section impact. An earlier study by Szalay (1989) measured the drag coefficients of a 16-sided polygon and compared the results with 4-sided and 12-sided polygons and circular cylinders in uniform flow conditions. The difference between sharp and rounded edges for the 16-sided polygons was insignificant. In a similar study, Jang and Chien (2009) conducted a series of CFD modeling to study the effects of changing the number of sides of a polygon while maintaining the cross-section aspect ratio (B/D) as 1. They carried out their simulations under the atmospheric boundary layer (ABL) wind profile rather than the uniform profile used in Szalay's research. As expected, the ABL tests resulted in relatively higher coefficients and loads compared to the uniform wind, but the trend between these two studies was the same, i.e., increasing the number of sides reduced the drag coefficient. Tang, Xie, Felicetti, Tu, and Li (2013) measured the drag force acting on the polygonal tower with different sides and rounded corners. They considered two shape-control factors: the number of sides and the radius of rounded corners (see Table 1). The results showed that the drag coefficient reduces as the number of sides increases. It was also noticed that the decrease in the drag coefficient was smaller when the number of sides was more than 14. Regarding the difference between a square tower and a rounded-corner tower, it was observed that corner roundness is an effective way to mitigate wind-induced loads, as shown in Table 1.

Table 1
Effect of roundness in reducing the drag coefficient (data extracted from Tang et al. (2013)).

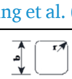
C_D	 r/b
1.58	square
0.93	0.10
0.36	0.25
0.38	circle

Table 2 lists the results from past experimental and numerical studies to evaluate cross-section effects on tall buildings' aerodynamic performance. This comparison helps to explore more about the building's shape effect on the aerodynamic coefficients.

One of the major aspects of the buildings is the likelihood of wind approaching the building from different directions. As such, the influence of the angle of attack (AOA) should be taken into account for aerodynamic performance evaluation. Table 3 summarizes results from some past studies that assessed the AOA impact. For instance, in a study by Obasaju (1992), a rectangular CAARC standard building was tested at different AOAs using wind-tunnel experiments under uniform and ABL wind profiles. As shown in Table 3, C_D and C_L results significantly vary with AOA, confirming its high impact on the building's wind loads. Similarly, Luo, Yazdani, Chew, and Lee (1994) studied the effect of AOA on square and triangular cylinders. They conducted wind tunnel testing with the uniform flow rather than ABL. The experiments indicated that none of the cross-sections is absolutely stable against galloping oscillation. It was noted that each model should be examined at the desired attack angle to prevent galloping instability.

In addition to the wind-induced loads, the effectiveness of aerodynamic modifications applied to a building model is also examined in terms of pressure distribution around the structure. For example, pressure distribution on a building façade can be affected by many factors, including incoming wind conditions, terrain type, surrounding structures, building geometry, and wind direction. There are commonly three different approaches used to determine pressure coefficients: full-scale field measurements, wind tunnel testing on a scaled model, and numerical simulation using computational fluid dynamics (CFD). Table 4 concisely lists past numerical and wind tunnel studies related to tall buildings investigating the aerodynamic characteristics or various building shapes and attack angles at the atmospheric boundary and uniform conditions.

As explained earlier, many studies have proven that building shape and wind direction considerably affect the wind loads and responses exerted on bluff bodies such as buildings. Several takeaway conclusions that could help shape future designs are summarized as follows:

- The most common trend is that the closer to circularity, the smaller the force coefficients achieved. However, these shapes are less popular considering the architectural and space design challenges they introduce. However, there are opportunities to design the future exterior façades with a more streamlined shape to minimize the flow separation and wake area due to sharp edges.
- It was observed that ABL conditions reflect more realistic results since they mimic actual atmospheric boundary conditions, even though higher loads (absolute values) have been measured with ABL testing. As a result, it is recommended that future studies consider testing building models with attachments or double façade systems under ABL wind to accurately assess their aerodynamic performance.
- In general, drag and lift coefficients differed considerably among studies for even similar aerodynamic shapes. This result was explained by models' dimensions, wind properties, and terrain conditions. Thus, passive solutions such as building shape modification may not always be effective over the life-cycle of the building because the design conditions such as environmental climate changes and new surrounding constructions are inevitable. This makes the justification for adaptive façades that could be an excellent choice to appropriately respond to such unpredictable conditions.
- It was found that wind direction significantly changes the aerodynamic loads exerted on tall buildings. This is another level of justification for consideration of smart and adaptive façades that could respond to changes in wind direction and overcome this challenging design parameter for tall buildings by adopting their shape to manipulate the wind-induced load and response.

Table 2
Review of numerical and experimental studies focused on cross-section effects.

Source	Exp.	Base Shape	Flow	Model Details	C_D	C_L	C_P	C_{ML}	C_{MD}	Other
Shiraishi, Matsumoto, Shirato, and Ishizaki (1988)	WT	Rectangle	Uni	(63.95×43.8) mm 1.46 *B/D*	1.8	0.00	–	–	–	2D model, Scale 1:80
Szalay (1989)	WT	Square	U	3:1 *H/B* 1.0 *B/D*	0.88	–	–	–	–	Scale 1:150 Tested Corner Facing Inlet
	WT	12-sided	U	3:1 *H/B* 1.0 *B/D*	0.65	–	–	–	–	Scale 1:150
	WT	16-sided	U	3:1 *H/B* 1.0 *B/D*	0.56	–	–	–	–	Scale 1:150
	WT	Circle	U	3:1 *H/B*	0.72	–	–	–	–	Scale 1:150
Dutton and Isyumov (1990)	WT	Square	ABL	(900×100×100) mm 1.0 *B/D*	–	–	0.60	–	–	Scale 1:400
Obasaju (1992)	WT	Rectangle	U	(732x183x122) mm 1.50 *B/D*	0.99	0.00	–	–	–	Short Side Scale 1:250
	WT	Rectangle	U	(732x183x122) mm 1.50 *B/D*	1.50	0.00	–	–	–	Long Side Scale 1:250
	WT	Rectangle	ABL	(732×183×122) mm 1.50 *B/D*	0.96	0.00	–	–	–	Short Side Scale 1:250
	WT	Rectangle	ABL	(732×183×122) mm 1.50 *B/D*	1.80	0.00	–	–	–	Long Side Scale 1:250
Luo et al. (1994)	WT	Triangle	U	(50×50) mm	2.10	0.00	–	–	–	2D model
	WT	Square	U	(50×50) mm 1.0 *B/D*	2.20	0.00	–	–	–	2D model
Igarashi (1997)	WT	Square	U	(30×30) mm 1.0 *B/D*	2.30	–	–	–	–	2D model
Jang and Chien (2009)	CFD	Square	ABL	1.0 *B/D*	1.70	0.85	–	–	–	–
	CFD	6-sided	ABL	1.0 *B/D*	1.20	0.85	–	–	–	–
	CFD	8-sided	ABL	1.0 *B/D*	1.01	0.80	–	–	–	–
	CFD	10-sided	ABL	1.0 *B/D*	0.85	0.75	–	–	–	–
	CFD	12-sided	ABL	1.0 *B/D*	0.90	0.80	–	–	–	–
	CFD	14-sided	ABL	1.0 *B/D*	0.87	0.80	–	–	–	–
Tanaka et al. (2012)	WT	Square	ABL	(400×50×50) mm 1.0 *B/D*	–	–	–	0.20	0.60	Scale 1:1000
	WT	Rectangle	ABL	(400×71×35) mm 2.0 *B/D*	–	–	–	0.33	0.80	Scale 1:1000
	WT	Ellipse	ABL	(400×80×40) mm 2.0 *B/D*	–	–	–	0.27	0.68	Scale 1:1000
	WT	Circle	ABL	*H*= 400 mm	–	–	–	0.03	0.37	Scale 1:1000
Tang et al. (2013)	CFD	Square	U	1.0 *B/D* Area= 100 m^2	1.57	–	–	–	–	2D Model
	CFD	6-sided	U	1.0 *B/D* Area= 100 m^2	1.15	–	–	–	–	2D Model
	CFD	8-sided	U	1.0 *B/D* Area= 100 m^2	1.25	–	–	–	–	2D Model
	CFD	10- sided	U	1.0 *B/D* Area= 100 m^2	0.90	–	–	–	–	2D Model
	CFD	12-Sided	U	1.0 *B/D* Area= 100 m^2	0.92	–	–	–	–	2D Model
	CFD	14- sided	U	1.0 *B/D* Area of 100 m^2	0.76	–	–	–	–	2D Model
	CFD	16-sided	U	1.0 *B/D* Area of 100 m^2	0.57	–	–	–	–	2D Model
	CFD	18-sided	U	1.0 *B/D* Area= 100 m^2	0.70	–	–	–	–	2D Model
	CFD	20-sided	U	1.0 *B/D* Area= 100 m^2	0.56	–	–	–	–	2D Model
	CFD	Circle	U	1.0 B/D Area= 100 m^2	0.42	–	–	–	–	2D Model
Wahrhaftig and Silva (2018)	CFD	Rectangle	ABL	(93×30×20) m	2.55	–	–	–	–	With small balcony
Alminhana, Braun, and Loredo-Souza (2018)	CFD	Rectangle	U	(185×45×30) m 1.5 *B/D*	2.43	1.20	–	–	–	–
Daemei et al. (2019)	CFD	Triangle	U	6:1 *H/B*, 120 m tall	0.79	–	–	–	–	–

Keynote: U: uniform flow, WT: wind tunnel experiment, CFD: computational fluid dynamics.

3. Aerodynamic shape modification

Recent studies indicate that wind loads can be noticeably reduced if the building shape is modified appropriately. Aerodynamic shape modification of tall buildings has been investigated using both wind tunnel testing and numerical simulations over the past decades. In order to provide a better understanding of how building shape impacts flow characteristics around these structures and provide a pathway for potential integration of these concepts in designing future DSFs, this section briefly reviews existing shape modification techniques and their effects on wind-induced loads on tall buildings. Aerodynamic shape modifications applied to reduce wind-induced forces and responses acting on tall buildings are generally divided into major and minor changes, as shown in Fig. 2. Major changes, referring to changes in overall building shape, include but are not limited to setback(s), opening (s), tapering, twisting, spoiler(s), multiple cross-sections, and double-cross section. These adjustments significantly impact structural and architectural features. The common underlying principle is to change

Table 3
Past wind tunnel studies considered the AOA effects on different building shapes (modified from Luo et al., 1994; Obasaju, 1992).

Source	Base Shape	Flow Type	Model detail (mm)	AOA°	C_D	C_L
Obasaju (1992)	Rectangle	Uniform	732 × 183 × 122 1.50 B/D (All cases)	0	1.49	−0.04
				5	1.50	−0.18
				10	1.45	−0.36
				15	1.38	−0.54
				75	0.81	0.44
				80	0.81	0.60
				85	0.94	0.30
				90	1.00	0.02
		ABL		0	1.79	0.00
				6	1.67	−0.30
				12	1.59	−0.53
				20	1.45	−0.59
				30	1.46	−0.41
				60	1.29	−0.30
				70	1.11	−0.14
				80	0.97	0.06
				90	0.97	0.04
Luo et al. (1994)	Square	Uniform	50 × 50 1.0 B/D (All cases)	0	2.19	0.00
				2	2.21	0.13
				4	2.20	0.32
				6	2.09	0.44
				8	1.91	0.50
				10	1.77	0.57
				12	1.64	0.82
				14	1.68	0.77
				16	1.80	0.54
				18	1.94	0.35
	Triangle			0	2.11	–
				5	2.11	0.18
				10	2.14	–
				15	2.11	0.64
				20	2.07	0.91
				24	1.86	0.88
				30	1.44	0.91
				34	1.44	0.91
				38	1.46	0.80

the flow pattern around the primary structure to generate incoherent vortices along the height, modify flow separation, and disrupt vortex shedding on the wake. On the other hand, changing the cross-section, referring to minor modification (see Fig. 2), is another strategy for improving the building geometry in the early design stage. This approach helps to streamline the tall building bluff body structures to reduce buffeting and aeroelastic loads. These strategies are included but not limited to slotted corners, chamfered corners, corner recession, and corner roundness, to name a few (Bandi, Tanaka et al., 2013; Elshaer, Bitsuamlak, & El Damatty, 2014; Iqbal & Chan, 2016). More details about these modification approaches can be found in a recent state-of-the-art review paper (Jafari & Alipour, 2020).

Tanaka, Tamura, Ohtake, Nakai, and Kim (2012) performed a series of wind tunnel experiments to measure aerodynamic forces and wind pressure on a tall building model with a square plan with various improvements. Seven shapes were considered for evaluation, including basic, corner modification, tilted, tapered, helical, openings, and composite models. The results of major shape modifications found by Tanaka et al. (2012) will be presented in this section, while the effects of minor changes described in that study will be discussed later. For the major modifications, the 4-tapered and setback models performed better in terms of the maximum mean overturning moment coefficient in the along-wind direction. The helical and cross-opening with $h/H = 11/24$ performed better in the across-wind direction. It was also observed that combined models with multiple modifications generally exhibited better aerodynamic performance than those for single modification cases. Vortex shedding for the square models occurred at almost the same time along the height, while it varied with height for setback and 180° helical models. In general, all models exhibited a high correlation between mean and fluctuating coefficients in both along- and across-wind directions (Tanaka et al., 2012). The experimental results obtained by Tanaka et al. (2012) are summarized in Fig. 3.

A similar study dealing with major modification conducted by Kim et al. (2014) tested 13 super-tall building models with atypical shapes in a boundary layer wind tunnel. Wind-load effects on the peak normal stresses were compared across the different modification approaches (see Fig. 3). Five models of the thirteen major modifications had single modifications, and five models had combined multiple adjustments. The square building model was used as the reference case. Since corner change is considered a minor correction, chamfered corners and corner-cut models will be discussed in the next section. The largest peak tensile stress for different models relative to the square model is shown in Fig. 3. The largest peak tensile stresses, about 11 kN/cm^2, belonged to the square model, the reference model. The results show that the square shape had the largest normal peak stress among all models. The largest normal peak stress of models with multiple modifications was generally smaller than single modification models. According to the obtained results, the building models with corner-cut, tapering, and 360° helical shapes had the smallest peak stress. Among the single modifications, the setback model had the lowest peak stress. It was found that the addition of corner-cut and 180° helical had a negligible effect in multiple adjustments, and the peak normal-stress exhibited minimal changes with the attack angle in multiple-modification models (Kim et al., 2014).

For twisted models, Tang et al. (2013) investigated one twisted square building based on the assumption that twisted bodies usually produce less drag. They compared straight polygonal towers and evaluated the impact of two parameters, including the number of polygon sides and the round corner radii. The wind speed, airflow density, and floor plan area were kept constant to compare the drag force. Fig. 4 illustrates the drag changes versus the twist angles at two wind directions. The results indicate that the drag drops slowly after the twist angle of 67.5°. The highest drag reduction of a twisted building compared to a straight building is about 6 %. Another advantage of twisting is changing the Strouhal number with height resulting from variation in the shedding frequency (Irwin, 2008, 2009). While twisting can be a reasonable choice for avoiding undesirable across-wind force from vortex shedding, the numerical simulations reflected nearly insignificant drag reduction for twisted towers. However, the twisting approach tends to narrow down the drag force change as wind direction varies (Tang et al., 2013).

Daemei, Khotbehsara, Nobarani, and Bahrami (2019) investigated seven triangular buildings (Fig. 5) through CFD. The study includes three major modifications and three minor corner modifications, and a building with no change used as the base case. Three major changes, consisting of setback, tapered, and helical, are discussed here, and the other cases, including chamfered, rounded, and recessed corners, are discussed in the next section. This study aimed to analyze wind effects and determine the best building shape in terms of appropriate aerodynamic behavior. They observed an almost 6 % error while performing validation with experimental data obtained by Fadl and Karadelis (2013). As illustrated in Fig. 5, the results indicate that tapered and setback models exhibit the best aerodynamic performance due to having the lowest drag coefficients, 0.60 and 0.62, respectively. The tapered model exhibits a 24 % reduction in drag coefficient compared to the basic model, while the setback model exhibits a decrease of approximately 21 %. On the other hand, the helical modification increased the drag coefficient to 1.00, while the drag coefficient of the basic model was 0.79 under the same conditions, so it can be concluded that the tapered and setback modifications for triangular case are the most effective forms of major aerodynamic designs.

The findings of several other studies on major modifications are summarized in Table 5 to provide an insight into the effect of the building's overall shape on aerodynamic performance.

The impact of changing the overall building shape was discussed in this section. Understanding such effects is essential for designing the

Table 4
Past studies using experimental and numerical techniques to investigate tall building aerodynamics.

Reference	B (cm)	D (cm)	H (cm)	Cross section	Modified Shape	α°	θ°	Terrain (α)	Tech	Measurements/ Results
Kwok and Bailey (1987)	6	6	54	SQ, ST	SC, FN, VNT	0	0	0.15	WT	PSD, Dis
Hayashida and Iwasa (1990)	8–12	8–12	60	SQ, TR, CR, Y	SC, RD, RS	0, 45	0	0.25	WT	C_D, PSD, Dis
Miyashita et al. (1993)	13	13	79	SQ	SC, OP, TO, CF, RS	0–45	0	0.15	WT	C_F, PSD
Cooper et al. (1997)	40	40	250	SQ	SC, TP, CF	0	0	0.2	WT	C_F, PSD, Dis
Kawai (1998)	5	5	50	SQ, CR	SC, CF, RS, RD,	0	0	0.2	WT	PSD, Dis
Tamura and Miyagi (1999)	50	50	30	SQ	SC, CF, RD	−5–+50	0	Un	WT	C_D, C_L, PSD, *St*
Kim and You (2002)	4,6,8,10	4,6,8,10	40	SQ	SC, TP	0–60	0	0.15, 0.30	WT	PSD, Dis, C_F
Zhou, Kijewski, and Kareem (2003)	5.1–15.24	5.1–15.24	40.6–53.3	SQ, TR, RM	SC, RC	0	0	0.16,0.35	WT	PSD
Gu and Quan (2004)	67–300	67–100	180	SQ	SC, RC, CF, CN	0	0	Cat A, B, C, D (China)	WT	PSD, ζ_a, Dis,
Kim, You, and Ko (2008)	54,64,72,80	54,64,72,80	32	SQ	SC, TP	0	0	0.15	WT	Dis
Dagnew and Bitsuamlak (2010)	11.4	7.6	45.7	–	SC, RC	0	0	0.16	CFD, WT	C_p
Kim and Kanda (2010b)	10	10	40	SQ	SC, TP, SB	0–45	0	0.13, 0.24	WT	C_p, C_D, $C_D^{'}$, C_L, $C_L^{'}$, PSD, Co, *St*
Huang, Lau, Chan, Kwok, and Li (2011)	11.25	7.5	45	RC	SC	0	0	0.15	WT, CFD	C_p, $C_p^{'}$, TKE, VF
Kim, Kanda, and Tamura (2011)	10	10	40	SQ	SC, TP, SB	0	0	0.13	WT	PSD, Acc, Co
Tanaka et al. (2012)	5	5	40	SQ, EP	SC, TP, OP, TW, SB, RC, CR, CF, CC	0–90	0,180,270,360	0.27	WT	C_P, C_D, C_L, M, PSD, *St*
Zheng and Zhang (2012)	16.2	16.2	60	SQ	SC	0	0	0.22	CFD	C_p, C_D, C_M, TKE
Zhengwei, Yong, Ming, Nankun, and Yong (2012)	5	5	60	SQ	SC	0–45	0	Cat B, D	WT	C_M
Bandi, Tanaka et al. (2013)	7.6 edge	7.6 edge	40	TR, Y, Clover	SB, TW, CF	0–120	0,60,180,360	0.27	WT	C_M, C_D, $C_D^{'}$, C_L, $C_L^{'}$, PSD, *St*
Carassale, Freda, and Marre-Brunenghi (2013, 2014)	5–15	5–15	50	SQ	SC, RD	0–45	0	Un	WT	C_D, C_L
Kim et al. (2014)	5	5	40	SQ	SC, TP, SB, OP, MS, TW, CF, CC	0–90	0,90,180,360	0.27	WT	S, M, F
Menicovich et al. (2014)	7	3.5	52.5	–	SC, RC	0–90	0	0.11,0.15, 0.25	WT	C_F, *St*
Gu, Cao, and Quan (2014)	7.5	7.5	60	SQ, ST	SC, TP, CF	0	0	0.22	WT	ζ_a
Aboshosha, Elshaer, Bitsuamlak, and El Damatty (2015)	30.48	30.48	182.2	SQ	SC	0	0	0.33	CFD	PSD, Co, Dis, Acc
Kim, Bandi, Yoshida, and Tamura (2015)	5	5	40	TR, SQ, PTG, HXG, OCTG, DDTG, CR	SB, TW	0–180	180	0.27	WT	M, PSD, Dis
Tominaga (2015)	B	B	2B	SQ	SC	0	0		CFD	PSD, TKE
Zhang, Habashi, and Khurram (2015)	11.4	7.6	45.7	-	SC, RC	0	0	0.28	CFD	C_P, C_F, Dis, Co
Liu and Niu (2016)	D	B	2B	SQ	SC	0	0	0.27	CFD	VF, PSD
Elshaer, Aboshosha, Bitsuamlak, El Damatty, and Dagnew (2016)	11.4	7.6	45.7	-	SC, RC	0, 90	0	0.17	CFD, WT	VF, C_p, M, PSD
Cui and Caracoglia (2017)	4.7	7.1	28.4	-	SC, RC	0–90	0	Un	WT	C_M, C_D,C_L,PSD
Zheng, Xie, Khan, Wu, and Liu (2018)	11.8	11.8	60	SQ, Y	SC, RS, CF	0–60	0	0.22	WT	PSD, Dis
Yu, Yang, and Xie (2018)	15	10	60	RC	SC	0	0	0.22	CFD, WT	C_p, $C_p^{'}$, PSD, M, Dis
Meng et al. (2018)	45.72 m	30.48 m	182.8m	RC	SC	0	0	0.27	CFD	C_P
Li, Tian, Tee, Li, and Li (2018)	10	10	80	SQ, RS, CF, RD	SC	0–90	0	0.22	WT	C_p, C_D, $C_L^{'}$, PSD, M, Co

(continued on next page)

Table 4 (*continued*)

Reference	B (cm)	D (cm)	H (cm)	Cross section	Modified Shape	α°	θ°	Terrain (α)	Tech	Measurements/ Results
Bairagi and Dalui (2018)	20	25	50	SQ	SC, SB	0–180	0	0.133	CFD	C_p

Keynotes: Acc: acceleration, CC: corner cut, CD: drag coefficient, CF: chamfered corner, CF: force coefficient, CFD: computational fluid dynamics, C_D: drag coefficient, C_L: lift coefficient, $C_L^{'}$: lift coefficient rms, C_M: moment coefficient, Co: coherence coefficient, C_p: pressure coefficient, $C_p^{'}$: pressure coefficient rms, CR: circle, DDTG: dodecagon, Dis: displacement, EP: ellipse, F: force, FN: fins, HXG: hexagon, M: moment, OCTG: octagon, OP: opening, PSD: power spectral density, PTG: pentagon, RC: rectangular, RD: rounded corners, RM: rhombus, RS: recessed corner, S: stress, SB: setback, SC: slotted corners, SQ: square, ST: straight, St: Strouhal number, TKE: turbulent kinetic energy, TO: through opening, TP: tapering, TW: twist, VF: velocity field, VNT: vented corner, WT: wind tunnel test, Y: Y shape, ζ_a: aerodynamic damping, α°: incident/attack angle, Tech: technique, θ°: twist angle.

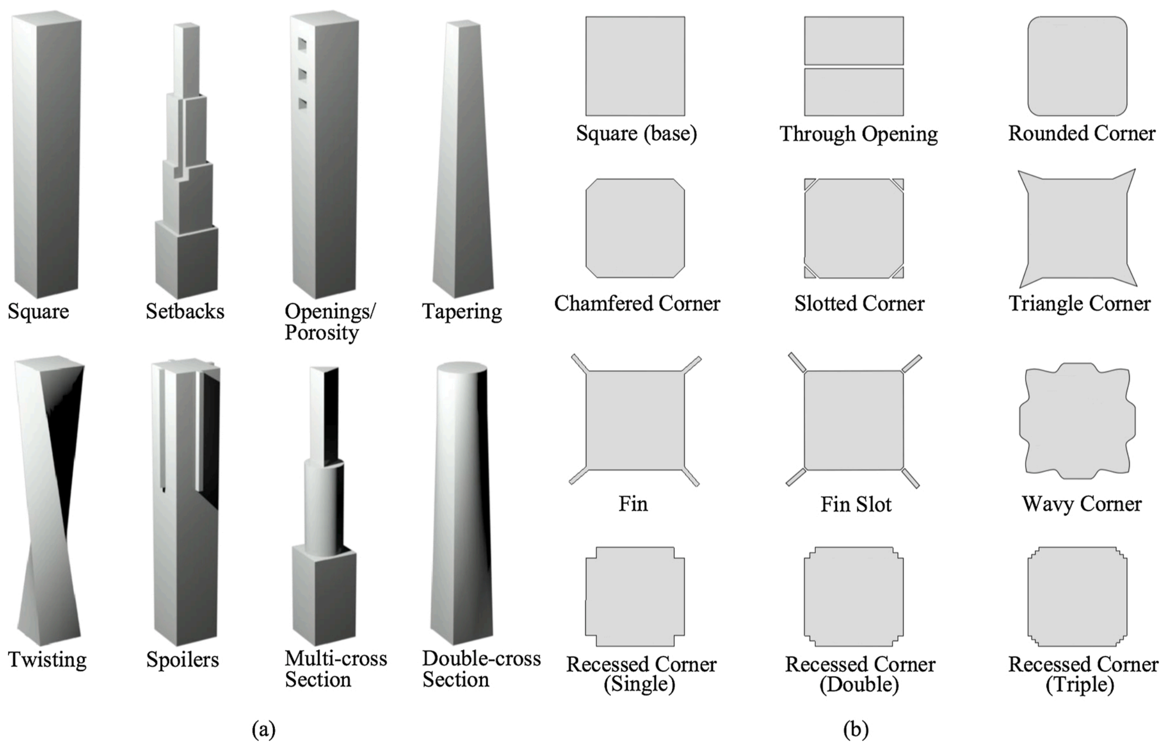


Fig. 2. Typical shape modifications used for tall buildings; (a) major, (b) minor.

aerodynamically effective façades that are either passive or adaptive. Although specific investigations are needed to evaluate the aerodynamic performance of DSFs, the studies reviewed in this section provide an initial point at the preliminary design stage. For instance, tapering and setback are the most effective approaches among major modifications that alleviate wind-induced loads and weaken vortex-shedding formation. Architectures can find beneficial inspiration from these approaches for designing aerodynamically efficient DSFs. As a result, these façades would be an excellent alternative for traditional modification approaches while maintaining energy-saving and ventilation applications. Similarly, the existing knowledge on major modifications can undoubtedly assist with developing sophisticated smart façade systems. For example, a smart façade, depending on the wind speed and wind direction, can change the overall building shape by deforming to a configuration similar to a combination of existing major modifications to optimize its aerodynamic performance.

Major changes mainly deal with the overall building shape, while the minor changes modify the building cross-section and corners. Modifying a building's corners is the most common approach to aerodynamically reshaping it. Several comprehensive studies discussed in the previous section have also assessed the effectiveness of corner modification. For instance, Tanaka et al. (2012) showed that the corner-cut and chamfered modifications result in better performance in both along- and across-wind directions. Kim et al. (2014) evaluated chamfered and corner-cut modifications on a square cross-section by comparing the largest peak tensile stresses and showed that the chamfered corner and corner-cut models performed better than the basic model (see Fig. 3). Furthermore, multiple modifications, including a couple of corner changes, exhibited smaller peak stresses than cases with only single modifications. However, comparing the results obtained for minor and major changes proves that the models with major changes performed better.

Daemei et al. (2019) investigated buildings with a triangular cross-section and various modifications. Compared to the basic triangular model with a drag coefficient of 0.79, rounded corners exhibited the most efficient performance in reducing the drag coefficient, reducing the drag coefficient by up to 66 % of the basic model. On the other hand, although the chamfered and recessed corner models exhibited relatively weaker aerodynamic performance than the basic model, their behavior was relatively close to the basic model. Eventually, it was concluded that using rounded corners as an aerodynamic solution to mitigate the wind load should be recommended for designing a tall building with a triangular cross-section and height greater than 120 m (Daemei et al., 2019).

In another study, Kwok, Wilhelm, and Wilkie (1988) experimentally evaluated the effects of modifying edge configurations on a tall

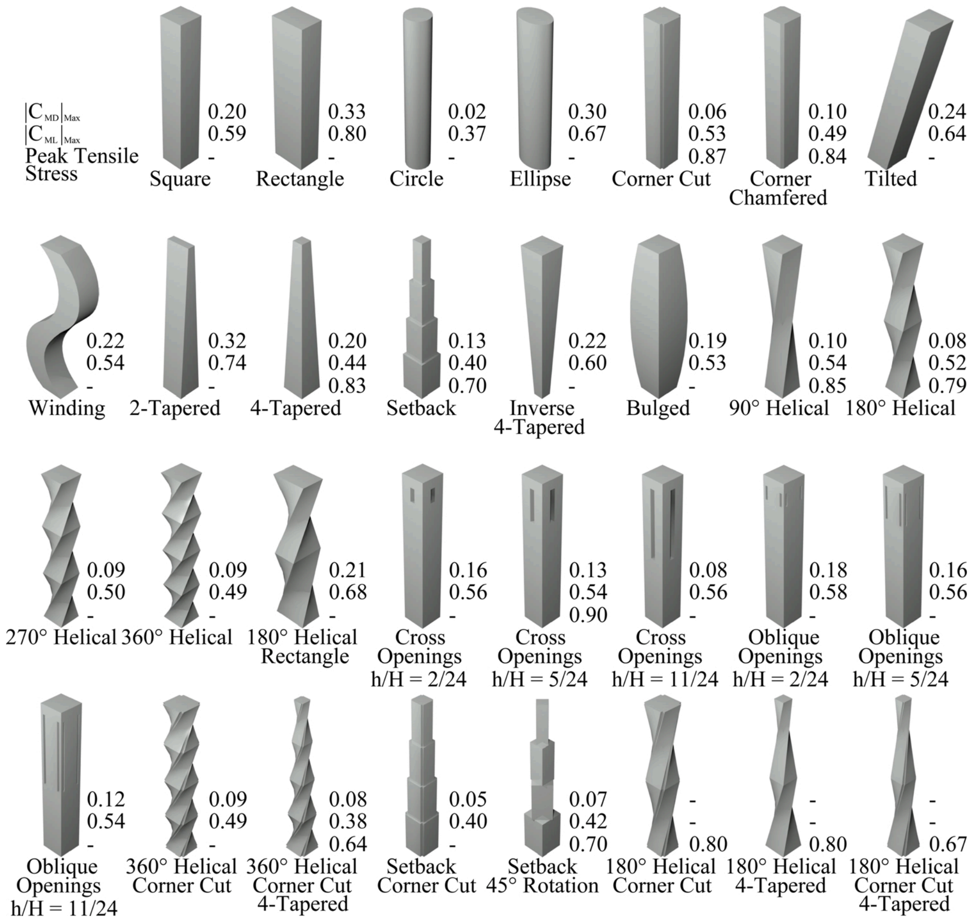


Fig. 3. Mean overturning moment coefficient and relative largest peak tensile stresses for different configurations edited and recreated from Kim et al. (2014) and Tanaka et al. (2012).

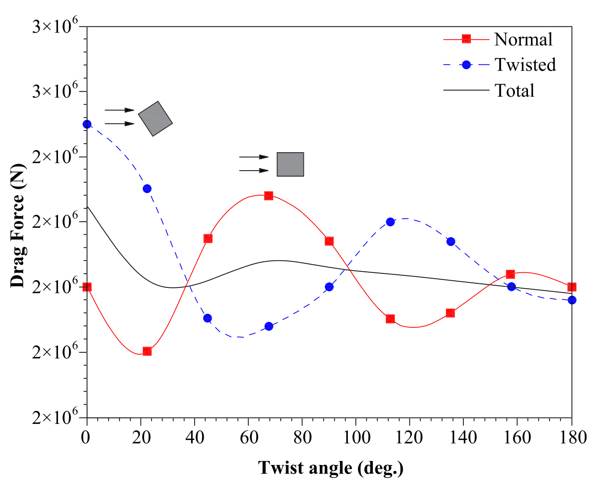


Fig. 4. Drag force acting on normal and twisted buildings (reproduced from Tang et al. (2013)).

building's wind-induced response with a rectangular cross-section. The reduced velocity, defined as $RV=U/nD$ (U is the wind speed, n is the natural frequency of structure, and D is the characteristic length varying between 4–20), and the damping ratio was set as 1 %. The results showed that the mean, standard deviation, and peak response were decreased significantly for slotted corners. While chamfered corners dropped the wind-induced displacement similarly to slotted corners, the chamfered case results were more prominent. Besides, it was found that the reduction could reach up to 40 % for chamfered corners compared with the plain section over the range of wind speeds tested. When wind faced the wide side of the building in their study, the across-wind response was significantly reduced by using slotted and chamfered corners; and the wind response was reduced by a factor greater than 2 when the reduced velocity was close to and above the critical "lock-in" regime. On the other hand, there was no significant response peak indicative of a dominant critical velocity effect observed as wind approaching a rectangular building's narrow side. In that case, the slotted corner response exhibited a 30 % reduction. The chamfered corner showed a larger reduction, up to a factor of 2 at the mid to high ranges of the reduced velocities tested. Slotted and chamfered corners also disrupted the vortex shedding that resulted in lowering the cross-wind response. Kwok et al. (1988) assessed the impact of wind direction changing from 0° to 90° at the reduced velocity of 10. A similar trend was captured for other reduced velocities of 6 and 15. It was found that the separated shear layer tends to reattach to the windward face of the building and decreases excitation as the attack angle increases.

Aeroelastic instabilities such as vortex-induced vibration and galloping phenomenon are common in tall buildings and must be considered during the design process. Kawai (1998) employed a boundary-layer wind tunnel to investigate the influence of corner modifications and roundness on vortex-induced excitation and galloping oscillation of aeroelastic square and rectangular prisms. The experiment was performed on 15 square and 11 rectangular prisms with side ratios of 0.5, as shown in Fig. 6. Circular and elliptical shapes were also tested for comparison. Kawai (1998) observed that corner roundness was the most influential factor in suppressing wind response for square prisms. Small corner cuts and specific recessions were very effective in reducing

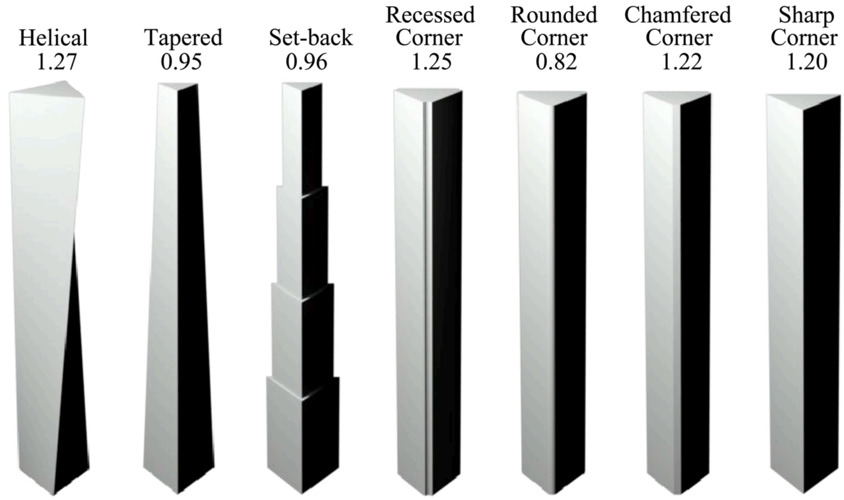


Fig. 5. Configuration of tested models and the maximum peak for drag coefficient reported (reproduced from Daemei et al. (2019)).

instability. In contrast, larger corner-cuts and recessions promoted instability at low velocity to decrease the onset of critical wind speed for galloping. For rectangular prisms, corner roundness had no influence on instability for damping ratios ranging from 0.2 % to 1.2 %, but larger roundnesses, corner cuts, and recessions effectively reduced instability when the damping ratio reached 4 %. Kawai (1998) also noticed that while corner modification has little effect on the wind-induced response, it could significantly decrease wind response at higher velocity.

A recent study by Elshaer et al. (2014) was focused on mitigating the drag force through minor aerodynamic changes for square buildings. They applied five different corner modifications and evaluated them using CFD simulations, and they finally compared the results with wind tunnel data. It was concluded that the sharp-edged square model produced the widest and longest wake, and the rounded-corner case exhibited the best performance among all cases. It was observed that the drag coefficient could be reduced by up to 40 % with rounded corners, and among all the studied models rounded-corner model had the lowest absolute pressure coefficients for the front and back faces. In contrast, the sharp-corners model exhibited the highest pressure coefficients. According to the results, the rounded-corner shape was reported as the best performing modification among the minor changes tested (Elshaer et al., 2014). Finally, a summary of past studies of minor aerodynamic improvements for tall buildings is provided in Table 6 to explore their effects more.

Similar to major modifications, studying the minor modification impacts assists with designing a more aerodynamically-efficient shape for the façades. For instance, it is proven that the rounding corner amongst minor changes is the most effective approach. This adjustment can be applied to the double façade system to avoid sharp edges leading to less wake area and wind loading while still maintain the sharp edges in the interior envelope of the building. Similar to opening modification, the flow that passes the gap between the double façade and building wall can interrupt the vortex-shedding generation and weaken its effects. Such similarities for the flow mechanism and shape effect encourage applying the existing aerodynamic-modification knowledge for designing passive or adaptive DSFs.

4. Surface roughness and building response

Roughness may originate from balconies, double façade systems, or other attachments on building envelopes. The roughness effect on moderate to tall buildings has been investigated in the past. For this purpose, past studies on roughness impact are briefly discussed here to explain how increasing building roughness influences wind-induced pressure and loading. Changing the building aerodynamics through surface roughness can be divided into passive and active approaches, as discussed in the following sections.

In a pioneering study by Chand, Bhargava, and Krishak (1998) on the effects of balconies, similar to those from adding roughness, a moderate-height building was tested through a series of wind tunnel experiments. The results showed that balconies altered the wind-pressure distribution on the windward side, while suction insignificantly increased on the leeward side. They also observed small changes in the aeromotive forces across openings on the third floor compared to those on other floors. A later study by Montazeri and Blocken (2013) showed that the effect of balconies on the oblique flow, such as wind approaching with 45°, was much more complicated than perpendicular flow, and they significantly changed pressure distribution around the building. Zheng, Montazeri, and Blocken (2020) used computational fluid dynamics (CFD) to capture the flow around the buildings with balconies concluded that buildings could exhibit excessive-high wind-nuisance levels with balconies.

Maruta, Kanda, and Sato (1998) performed wind tunnel experiments to track drag-force changes due to the building's surface roughness. In their experiments, they varied the roughness of building exterior walls with sandpaper and the addition of balconies with and without mullions and changed the angle of attack from 0° to 20° with a 5-degree interval. The results indicated that the wind pressure was significantly affected by surface roughness that weakened the strong fluctuating pressure, particularly near the leading edge. Due to the surface roughness increase, local peak pressure decreased, and incremental roughness restrained conical vortices' development for fluctuating wind pressure. In general, surface roughness, such as that from window sashes, wall textures, and balconies, reduced the peak pressures leading to mitigate the drag force (Maruta et al., 1998). The idea that roughness could efficiently reduce wind load on buildings has led to more recent studies considering the addition of attachments represented by balconies in real conditions to provide surface roughness and reduce aerodynamic loads on tall buildings.

Stathopoulos and Luchian (1990) tested a scaled building with attachments to evaluate the impact of balconies representing surface roughness on the wind pressure. In their experiments, they generated the ABL wind profile belonging to the country and urban terrains. The results indicated that except for the lower region of the side and leeward faces, attachments slightly influenced the wind pressure and the windward face's upper region. The pressure was reduced in these areas by increasing surface roughness produced by these attachments. A similar trend for the cladding was reported for mean and fluctuating wind loads. Maruta et al. (1998) measured wind pressure through wind tunnel testing under uniform flow and boundary-layer wind profiles in urban

Table 5
Previouse studies on major aerodynamic modifications of tall buildings.

Reference	Major Modification	Remarks
Dutton and Isyumov (1990)	Opening	They observed a reduction in across-wind excitation especially a large wind response reduction for gap d/D = 4 %. This reduction was explained through disruption to the organized and narrow-band vortex shedding.
Miyashita et al. (1993)	Opening	The crosswind fluctuating wind force for building with openings was lower than the original square cross-section.
Kim and You (2002)	5 %, 10 %, 15 % tapering	The tapering reduced the across-wind response more than along wind response, while response reduction may not always reach. Tapering is more effective in suburban terrain.
Kim et al. (2008)	5 %, 10 %, 15 % tapering	Tapering showed higher effectiveness at high reduced frequencies and moderate damping ratio ranging from 2 to 4 %. However, tapering may adversely affect wind response at low damping.
Kim and Kanda (2010b)	5 %, 10 % tapering, setback	Both tapering and setback reduced the mean drag and fluctuating lift forces. As the tapering ratio increased, the reduction ratio increased, and the setback was more effective in reducing the fluctuating lift force than the tapering.
Kim and Kanda (2010a)	5 %, 10 % tapering, setback	Tapering and setback can modify the flow pattern around a tall building, and mean drag and fluctuating lift forces were decreased considerably due to these modifications.
Kim et al. (2011)	5 %, 10 % tapering, setback	Modified models with mass center and rigidity center eccentricity reduce along-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.
Bandi, Tamura, Yoshida, Kim, and Yang (2013)	60°, 180°, 360° helical	A reduction in maximum mean and fluctuating overturning-moment coefficients was captured for both along- and across-wind directions.
Kim and Kanda (2013)	5 %, 10 % tapering, setback	The bandwidth of power spectra and the position of peak frequencies are highly influenced by tapering and setback modifications. They found that vortex shedding occurs more in the building's upper region, and the vortex formation height moves upward.
Deng, Yu, and Xie (2015)	2.2 %, 4.4 %, 6.6 % tapering	Adding tapering ratio resulted in increasing vortex shedding frequency and reducing vortex shedding energy. Thus, the across wind-induced load and response reduced.

terrain. To assess the impact of surface roughness, they tested the building with roughness and three types of balconies. It was found that a building's surface roughness significantly influences the wind pressure, particularly close to the leading edge of the sidewalls, where the peak pressure was reduced the increasing roughness.

A recent study by Yuan, Hui, and Chen (2018) assessed the influence of attachments on the pressure field around a high-rise building by testing 21 different configurations using wind tunnel testing. The study mainly focused on the effects of horizontal extension with varying depth ratios of the attachment with respect to the building dimension. The additional attachments were only added to the building's upper part, as it was considered a critical section of the building in controlling the negative peak pressure. Fig. 7 demonstrates their models, including their

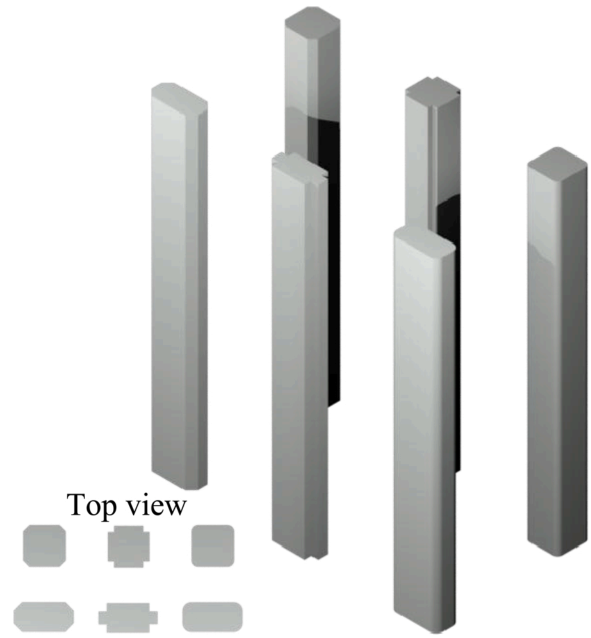


Fig. 6. Section models with corner cut, recession, and roundness modifications (reproduced from Kawai (1998)).

"Ref" model defined as the reference case without any attachment, with models A1, B1, C1, and D1 having continuous plates with different vertical separations. Models A2, A3, and A4 have discontinuous plates with various horizontal gaps. The AOA varied from 0° through 45° at 5-degree intervals. The results obtained by Yuan et al. (2018) indicated that the attachments did not significantly affect the pressure distribution or the maximum pressure coefficient, C_{pmax}, except for two of the models (B1 and C1) with the largest extensional depth of the thin plates. They also reported that the larger attachment depths resulted in stronger effects on the flow pattern as decreasing this depth weakens the multi-stagnation phenomenon observed in their study. Since the maximum reduction in positive peak pressure was less than 27 %, it can be concluded that the attachments did not significantly change the C_{pmax}. However, the minimum pressure coefficient at the upper leading edge dropped by 20 %–40 % with attachments.

Based on the study by Hui, Yuan, Chen, and Yang (2019) and Yuan et al. (2018) found that both continuous and discontinuous attachments had little to negligible impact on fluctuating pressure coefficients of the windward side. The attachments decreased fluctuating wind pressures at each level but increased the mean coefficients at the lower part of the side façade. In general, a discontinuous attachment led to slightly larger along-wind mean forces than the original model but had a negligible effect on the fluctuating forces. For the base moment, discontinuous attachments reduced the fluctuating across-wind base moment by up to 5 %, while continuous ones increased this value by up to 8 %. Finally, they concluded that the addition of horizontal attachments favorably organized the vortex-shedding formation. Lignarolo, Lelieveld, and Teuffel (2011) evaluated the effectiveness of surface roughness in manipulating the wind-induced pressure around tall buildings. To this end, they tested the three high-rise models with different configurations depicted in Fig. 8. These models include smooth-surface (A2), horizontal-roughness (B2), and vertical-roughness elements (C2). The smooth-surface models (A2) were the same as B1 and B2 models but with no attachments.

For both the base model and the model with roughness, the validation results obtained by Lignarolo et al. (2011) matched well with those presented by Chand et al. (1998). They found apparent differences between the two pressure fields of models A1 (smooth wall) and A2, especially at the top and ground floors. The velocity fields of the

Table 6
Past investigations on minor modification of building cross-sections.

Reference	Minor Modification	Remark
Kwok and Bailey (1987)	Vertical fins, vented fins, corner slots	The slot corner substantially decreased wind response in both directions. Installing fins increased along-wind response and reduced the crosswind response only for a limited range of reduced wind velocities.
Kwok et al. (1988)	Chamfering, corner, and horizontal slots	The modifications and their combinations had a considerable impact on along- and across-wind responses. The spectrum analysis proved that chamfered adjustment majorly changed the excitation frequency and magnitude.
Hayashida and Iwasa (1990)	Corner cut, rounding	They found that variation in the cross-section shape alters the aerodynamic damping of tall buildings.
Miyashita et al. (1993)	Chamfering, recession	A reduction in the fluctuating force component along the across-wind direction was observed for the normal incidence angle.
Tamura, Miyagi, and Kitagishi (1998)	Chamfering, rounding	They decreased the wind response in both directions. Such corner adjustments resulted in a 60 % reduction drag coefficient compared to the original shape. CFD techniques successfully predicted the flow around the building.
Kawai (1998)	Chamfering, recession, rounding	Corner rounding has more effect on aerodynamic modification than chamfering and recession. Small corner-cut and recession increased the aerodynamic damping; however, large changes promoted aeroelastic instability at low wind speed. Rounding corners were also influential in mitigating the instability.
Tamura and Miyagi (1999)	Chamfering, corner-cut, rounding	All modifications resulted in reducing the drag force to the promotion of reattachment and reduction of wake width.
Gu and Quan (2004, 2011)	Chamfering, recession	They compared the results for lots of modifications. They studied the aerodynamic damping in the across-wind direction and derived a couple of formulas for across-wind force PSD, moment coefficient, and shear forces.
Tse, Hitchcock, Kwok, Thepmongkorn, and Chan (2009)	Chamfering, recession	According to the results, the recessed corners indicated more effective in reducing the vortex shedding excitation forces than the chamfered corners, particularly for the small recessions.
Zhengwei et al. (2012)	Single & double recession	They studied 14 square high-rise buildings with recessed corners. Both approaches mitigated the moment and torque coefficients. The most effective model belonged to building with a 7.5 % recession ratio.
Carassale et al. (2014)	Rounding corners	The critical angle of incidence decreased with rounding the corners. The intermittence behavior was also observed for rounded corners at critical incident angles.
Deng et al. (2015)	Chamfering, opening	Chamfering suppressed the crosswind vortex-shedding impact on buildings with tapering. The opening slot mitigated the vortex shedding strength.

high-rise models A2, B2, and C2 were compared, and it was observed that the roughness significantly affected the flow field. Moreover, the vertical direction's roughness elements provided a more uniform flow, and vertical roughness elements revealed extensive wind resistance and reduced the wind velocity closer to the façade. Conversely, flow canalization could be achieved when the roughness elements were turned to the horizontal direction. The addition of roughness to the façade also decreased vortices close to the upwind corner. Lignarolo et al. (2011) concluded that surface roughness could change a bluff body's aerodynamic properties, similar to a past wind-tunnel study by Maruta et al. (1998) that showed the effectiveness of surface roughness on changing aerodynamic drag force. In general, it can be concluded that although balcony design has other applications and architectural purposes, it may help to alleviate the mean or fluctuating wind components by changing the wind-induced pressure around the building due to an increase in the surface roughness. According to the studies discussed above, it is necessary to evaluate the aerodynamic performance of each design to ensure the positive or negative effects on tall buildings. The available literature on the effects of surface roughness provides an educated first estimate for the design of facades that recreate similar conditions with changing the roughness of the building envelope.

A suite of studies that have focused on the effects of roughness has used nature-inspired solutions to change the roughness of the building surface. For example, a large body of literature has looked into cactus-shaped roughness on the building surface. Since the cross-section of a cactus-shaped building is similar to a circular shape, studies on cactus-shaped structures have mainly been compared to circular models (Abboud, Karaki, & Oweis, 2011; Babu & Mahesh, 2008; Levy & Liu, 2013; Talley & Mungal, 2002; Talley, Iaccarino, Mungal, & Mansour, 2001; Yamagishi & Oki, 2005). The research conducted by Babu and Mahesh (2008) tested the drag reduction performance of cactus-shaped cylinders at low Reynolds numbers. It was observed that the total drag coefficient was reduced by around 22.5 % as viscous forces reduced. Extending the work by Babu and Mahesh (2008) and Letchford, Lander, Case, Dyson, and Amitay (2016) assessed the aerodynamic performance of bio-mimicry-inspired tall buildings using cactus shape through a series of wind-tunnel experiments. They investigated the Saguaro cactus-inspired cylinders to understand the impact of grooves on the wind response of tall and slender cylinders. As shown in Fig. 9, high aspect ratio (15:1) domed- and flat-top cylinders with smooth, roughened, and grooved surfaces were tested using an open-circuit wind tunnel. The domed-top model showed better aerodynamic performance compared to the flat one. In the atmospheric boundary layer wind profile, the cactus-inspired shape with 24 circumferential grooves reduced the mean and fluctuating drag by around 20 %, similar to what was observed by Talley and Mungal (2002). Furthermore, the mean drag and base moment coefficients were reduced by 20–30 % for the cactus shape compared to the smooth shape. The promising results reported by Letchford et al. (2016) encourage applying such roughness changes to modify wind loading on tall buildings and double façade systems. These results highlight the validity of using nature-inspired approaches to be

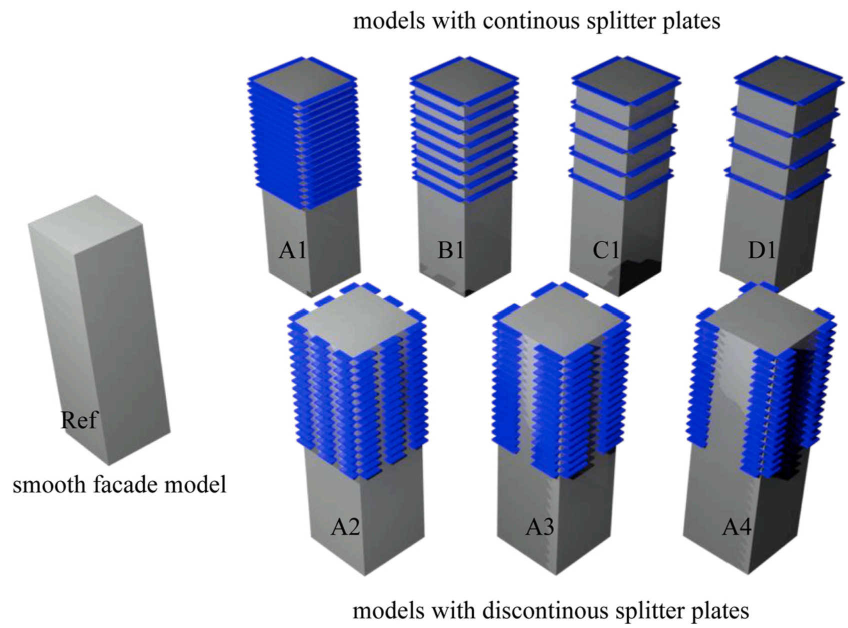


Fig. 7. 3D representations of the reproduced models studied by Yuan et al. (2018).

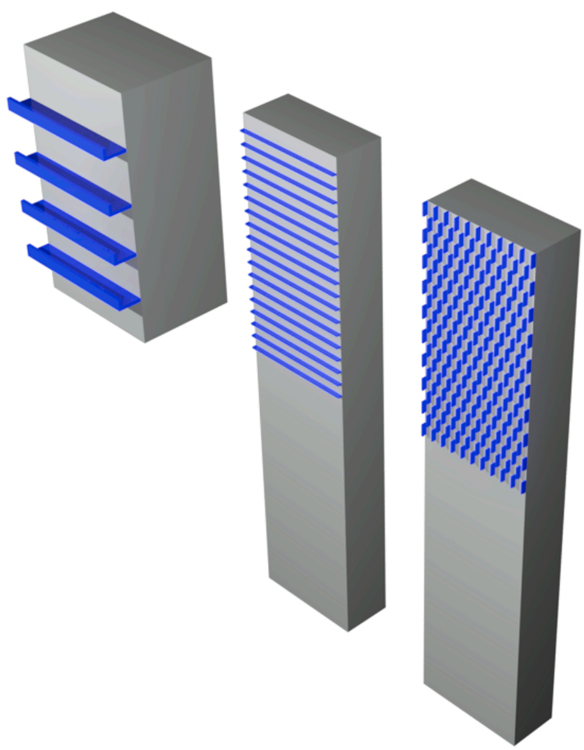


Fig. 8. Schematic view of reproduced models tested by Lignarolo et al. (2011); from left, models B1, B2, and C2, respectively.

integrated into the design of the building facades to control the aerodynamic forces.

5. Smart facades for wind mitigation

Active façade modification is a new and open research area investigated in only limited studies. Lignarolo et al. (2011) focused on fabricating façade systems from shape-morphing smart materials to adapt their textural material characteristics. This technology could manipulate the building's surface roughness, modifying the velocity field close to the façade surface. Smart materials were able to detect environmental changes and respond accordingly. In a new design for the façade system, Lignarolo et al. (2011) proposed a "smart" building envelope whose surface texture could be changed. Inspired by the fur of mammals and birds' feathers, a morphing envelope was designed to control building ventilation by changing surface texture. The proposed design involved small deflecting elements capable of opening and closing relative to wind direction and velocity. Each of these elements could be separately controlled to provide a diverse surface texture optimized for each height and speed. The advantage of using shape-deforming smart material in the adaptive façade elements is that small and light construction sizes can be achieved with deformations based on material properties. In a most recent study, a data-driven adaptive control strategy was developed that minimized wind-induced vibration by independently adjusting the angular orientation of an active façade system composed of a set of plates. Genetic Algorithm optimization was used to determine façade plate angles and alter the aerodynamics of the building (Abdelaziz, Alipour, & Hobeck, 2021) with the final goal of reducing the wind-induced vibrations. In another study, the facades for a rectangular and elliptical building shape were optimized to reduce the drag coefficient of a building under different AOAs (Jafari & Alipour, 2021).

Recent investigations prove that the double-façade systems can significantly reduce wind-induced load and vibration of tall buildings (Hu, Song, Hassanli, Ong, & Kwok, 2019; Moon, 2009). The aerodynamic modification generally originates from increasing surface roughness and creating a porous medium. Up to the present time, the number of research articles on the aerodynamic application of double-skin façades is small and inadequate compared to those on ventilation and energy-saving applications. The DSF can be integrated with other earlier-discussed aerodynamic modification techniques to overcome wind-related concerns in designing taller buildings. Hu, Hassanli, Kwok, and Tse (2017) studied the influence of a double-skin façade system on tall buildings' wind-induced response using a CAARC building scaled down to 1:400 for wind-tunnel testing to capture the wind response of an aeroelastic model. Apart from the baseline model, four other models with different porosities through vertical openings were tested, as shown in Fig. 10. Case 1 had a double-skin façade with no openings, and Cases 2-4 had a double-skin façade with vertical openings. Fig. 10 demonstrates the dimensions and four different cases of the tested double-skin façade by Hu et al. (2017). Along- and across-wind responses were measured using the strain gauge,

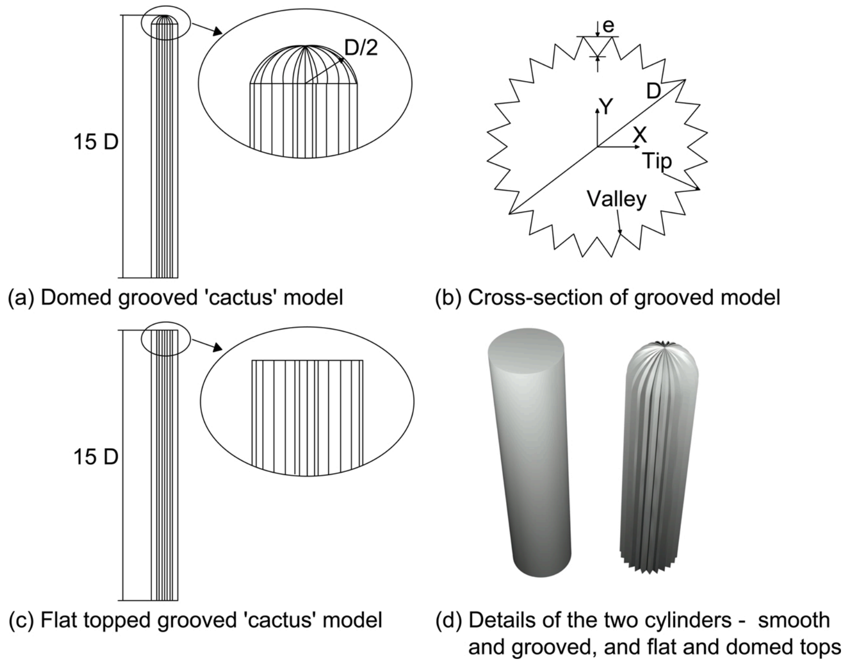


Fig. 9. Details of the cactus model studied by Letchford et al. (2016).

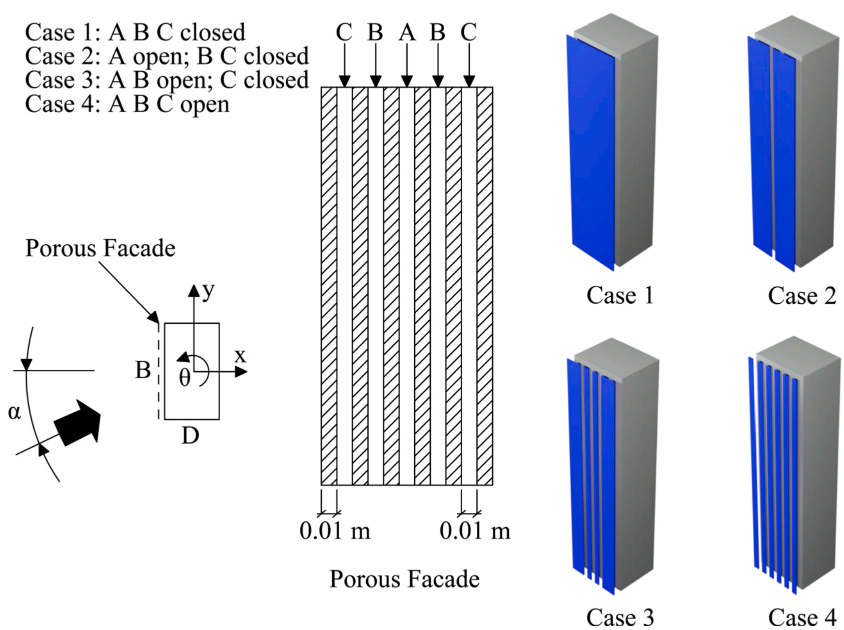


Fig. 10. Reproduced figure of the four different double-skin façade tested by Hu et al. (2017).

and the pressure measurement was performed for some cases.

The results indicated that the vertical opening in the double-skin façade had only a negligible effect on wind-induced response mitigation in the along-wind direction, but a significant impact was observed in the across-wind direction. Pressure-test results proved that the façade with no opening had the largest fluctuating pressure on the side faces. In contrast, the façade with openings reduced the fluctuating pressure, with openings at the center having the most significant effect on fluctuating pressure. They also used cross-correlation analysis to study the relationship between wind response and façade configuration along the building height. As shown in Fig. 11, the jet flow generated by façades interrupts the separated shear layer; therefore, the interaction between the shear layer and the side face is less intense, and the inside flow is less turbulent (Hu et al., 2017).

Giachetti, Bartoli, and Mannini (2019) investigated how a relatively thin screen could affect buildings' aerodynamic behavior. The reproduction of the cavity between the screen and the building was somewhat challenging to achieve in the wind tunnel. Since a three-dimensional study would be excessively complicated, Giachetti used an idealized two-dimensional model to represent a building with a permeable envelope. Both wind-tunnel tests in a smooth flow and CFD simulations were carried out for comparison, and two different screens were tested. As shown in Fig. 12, they included model S1 with only horizontal compartmentation created by spacers and model S2 with additional internal vertical compartmentation. For models with the S1 screen, the drag coefficient was slightly (approximately 10 % reduction compared

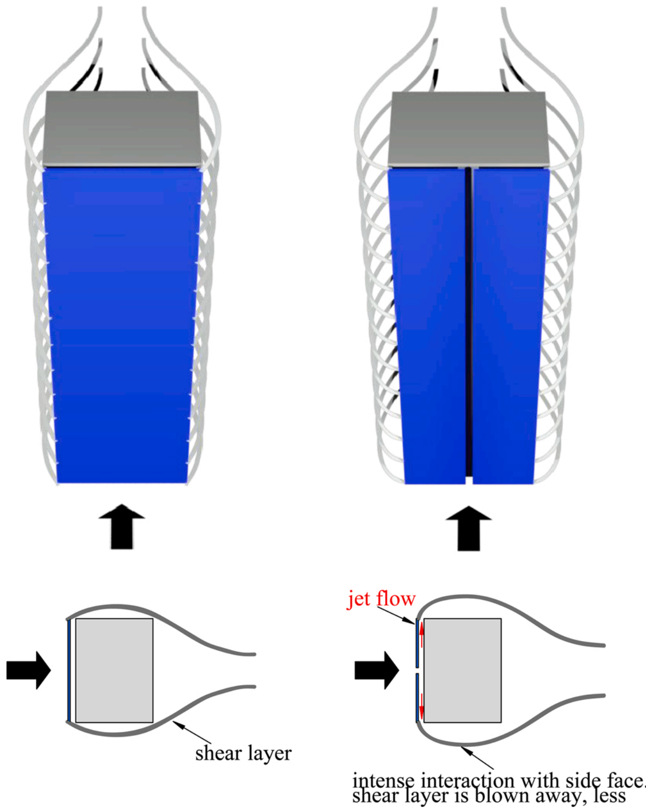


Fig. 11. Schematic view of cases without opening and with a central opening (reproduced from Hu et al. (2017)).

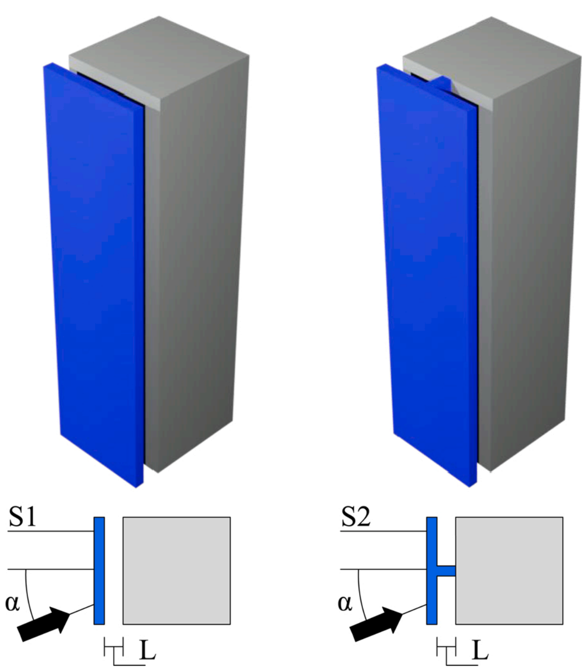


Fig. 12. Schematic view of the two models modified from Giachetti et al. (2019).

to the base model) affected by screens when the flow was perpendicular. The drag force increased monotonically with gap width. Regarding the screen's effect on pressure fluctuations, cases with small gaps showed higher pressure variations than those without a screen, and models with bigger gaps had lower standard deviation values. Eventually, they compared the CFD results using $k-\omega$ *SST* and Spalart–Allmaras (SA) turbulence models with wind tunnel data and observed an excellent match. In summary, it was concluded that either a double-skin façade or screen positively influenced a tall building's aerodynamics.

Hu et al. (2019) performed a series of wind tunnel experiments to assess the effectiveness of attached DSFs with vertical openings in the external skin to alleviate wind-induced pressure on the building's cladding. It was shown that a DSF without opening resulted in an increase in the mean suction pressure and fluctuating pressure on the leeward face and both sides, representing unsatisfactory performance by the double façade system under extreme wind conditions. Conversely, the pressure was reduced on the leeward face and sides for DSFs with the opening(s). Therefore, it was concluded that double-skin façades with openings could effectively improve the wind resistance of buildings if they are designed with vertical openings. Fig. 13 illustrates the different cases evaluated in their study. Kwok, Samali, Hu, and Tse (2014) tested a double façade system similar to case 4 shown in Fig. 13d for alleviating the wind response of tall buildings and tested this system using wind-tunnel testing. The data obtained proved that the along- and across-wind responses and the torsional excitation were considerably reduced by attaching the proposed DSFs with vertical openings.

Da Silva and Gomes (2008) tested DSFs with small to large gaps for a range of AOAs to evaluate their impact on a multi-story building. They concluded that the pressure coefficient inside a DSF's gap is always negative for all wind directions, similar to the results reported by Potangaroa and Aynsley (2003). They employed a solid façade with no opening, and experiments for AOAs varying between 0°–45° showed a significant impact on pressure distribution. Pomaranzi et al. (2020) performed a series of wind-tunnel experiments to study the aerodynamic performance of a porous double-skin façade and its effectiveness in reducing wind-loading on the cladding surface. They observed that a DSF could mitigate positive and negative peak pressures of the inner glazed façade by up to 40 %. Moreover, the DSF system acted as a filter for a pressure signal that positively influenced the mean and standard deviations. Başaran and İnan (2016) performed an experimental assessment to monitor pressure loss due to a double-skin façade using perforated plates by changing the Reynolds number while conducting the experiments on various perforated plates. Gerhardt and Janser (1994) carried out a parametric study that changed building geometry, façade porosity, and gap depth to explore each parameter's influence on wind load on a building covered with a double-skin façade. After validating their results by comparison with available experimental data, they presented the pressure coefficients for different cases. Gerhardt and Kramer (1983) investigated wind-permeable façades to capture the probability distributions of pressure coefficient and sensitivity of peak pressure with respect to incoming flow conditions.

Lou, Li, Wei, Chen, & Li (2008) and Lou, Zhang, and Shen (2009) compared wind-tunnel pressure results for circular and rectangular tall buildings covered by single and double-skin façades with arc-chape and L-shape configurations. Accordingly, the overall wind loads acting on buildings and façade did not significantly change after using these façades. Another study by (Lou, Jin, Chen, Cao, & Yao, 2005) compared wind-tunnel data with numbers provided by loading codes in China (GB50009-2001) for a rectangular tall building's double-skin façade. It was found that the shape coefficient for the square building given in the codes could be applied for the rectangular building if the wind is blowing parallel to the longer side of the building. However, a considerable difference was observed between experimental data and building code when the wind approached the shorter side. Lou, Huang, Zhang, and Lin (2012) applied numerical and experimental techniques to understand the wind-induced pressure on tall buildings with a double-skin façade. They measured pressure distribution for different layouts, angles of attack, and gap depths. They modeled the inner-gap pressures on double-skin façades using the zonal approach and concluded that zonal modeling was a suitable method that provided results consistent with CFD simulation. Taking advantage of CFD simulation, Montazeri,

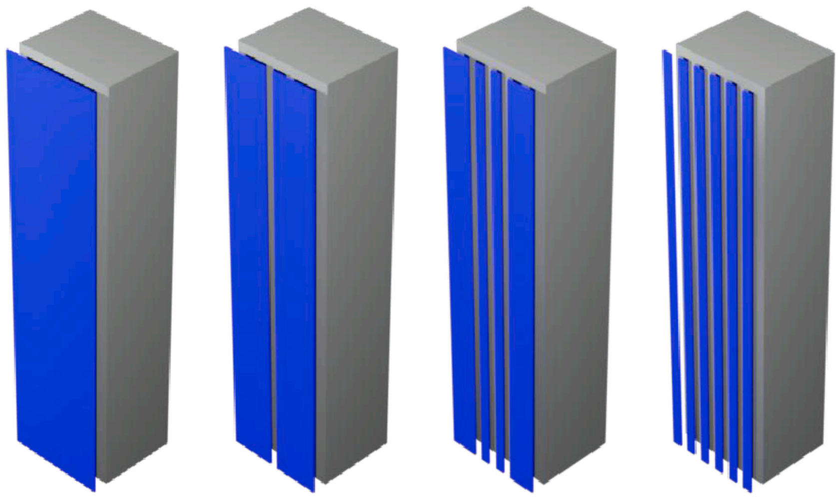


Fig. 13. Different three-dimensional DSFs studies by Hu et al. (2019) (modified and reproduced from Hu et al. (2019)).

Blocken, Janssen, and van Hooff (2013) assessed the efficiency of a staggered semi-open double-skin façade located in front of a balcony for improvement of wind comfort on high-rise buildings. They conducted a three-dimensional steady simulation using the Reynolds-Averaged Navier Stokes (RANS) model for buildings with and without the façade. Comparing the wind comfort results with the Dutch Wind Nuisance Standard showed that the local wind speed is noticeably mitigated due to pressure gradient drop across the façade width. All these inspiring results prove the effectiveness of DSFs in modifying aerodynamic performance of tall buildings and support of their usage as an aerodynamic solution to alleviate the wind-induced loads on tall buildings.

6. Architectural applications of adaptive facades and future opportunities

The continuous environmental changes result in new challenges for designing tall buildings that need to be addressed. Such structures are exposed to issues caused by weather change, solar radiation/light, wind, etc. Each building consumes a considerable amount of energy for heating, cooling, and lighting in order to respond to some of these external environmental changes (Lopez, Rubio, Martín, Croxford, & Jackson, 2015). As a result, it demands new adaptive approaches to properly overcome these environmental challenges instead of static or non-adaptive solutions. To this end, adaptive façades have recently gained considerable attention to enhance the building performance. Such innovative multifunctional systems can improve indoor environmental quality, reduce building energy consumption, and harvest renewable energy (Reynders, Nuytten, & Saelens, 2013). In fact, the adaptive façades used for high-rise buildings are the next significant milestone in façade technology due to their capability in interacting with the built environment and adjust their behavior and functionality based on external changes in real-time (Loonen, Favoino, Hensen, & Overend, 2017). It can be seen in the literature that other names have been interchangeably used instead of adaptive façades such as responsive (Kirkegaard & Foged, 2011), kinetic (Fox & Yeh, 1999), interactive (Fox & Kemp, 2009), advanced (Selkowitz, Aschehoug, & Lee, 2003), active (Xu & Van Dessel, 2008), dynamic (Lollini, Danza, & Meroni, 2010), intelligent (Ochoa & Capeluto, 2009), smart (Granqvist et al., 1998), and switchable (Platzer, 2003). The adaptive façades can be divided into two general categories of passive and active based on their operations. A majority of available adaptive façades are passive and do not require external energy for operation. However, they may not be as efficient as active adaptive façades that automatically react to environmental changes by changing their shapes.

The building envelope plays a crucial role in attaining a building's energy efficiency and good indoor comfort. Despite past developments in improving the building envelope's insulation to reduce energy loss, consideration of a building's overall energy demand and limitations in reaching the Zero Energy Building (ZEB) goals have urged revolutionizing the available façade design. Research indicates that limitations of existing façades can be resolved only by switching from static to responsive and dynamic systems, such as multifunctional façade modules (MFMs) (Hinsch et al., 2009; Nagy et al., 2016; Paiho, Seppä, & Jimenez, 2015; Vartiainen, Peippo, & Lund, 2000) and responsive building elements (RBEs) (Concepts, 2009; Favoino, Goia, Perino, & Serra, 2014; Favoino, Goia, Perino, & Serra, 2016; Goia, Perino, Serra, & Zanghirella, 2010; Heiselberg, 2009; Hinsch et al., 2009; Loonen, Hoes, & Hensen, 2014; Nagy et al., 2016; Paiho et al., 2015; Vartiainen et al., 2000). A summary on adaptive architectural envelopes are described in the literature, such as intelligent skin (Wigginton & Harris, 2002), adaptive skin (Hasselaar, 2006), acclimated kinetic envelope (Wang, Beltrán, & Kim, 2012), climate adaptive building shell (Loonen, Trčka, Cóstola, & Hensen, 2013), and adaptive building skins (Del Grosso & Basso, 2013).

The existing adaptive façade could continuously and proactively react to outdoor and indoor environmental conditions and exploit renewable and low-energy sources. Adaptive façades are multi-objective, high-performance envelopes that, unlike static curtain walls, respond mechanically or chemically to external climate dynamics to meet inside load requirements (cooling, heating, lighting, or ventilation) and occupants' needs (Loonen & Hensen, 2012; Loonen, Trcka, & Hensen, 2011; Loonen et al., 2013; Loonen, Singaravel, Trčka, Cóstola, & Hensen, 2014). The dynamic interactions bring a strong mutual dependence between design and control aspects (Liu, Zhang, & Van Der Spiegel, 2014), with performance dependent on the scheduling strategy (i.e., control logic) for façade adaptation during operation.

As mentioned above, dynamic adaptive façade systems have been designed and installed in the past decade. According to the continuously updated Climate Adaptive Building Shells (CABS) database (Kim, Lee, & Kim, 2013), there are now more than 500 examples of buildings with adaptive façades. It is expected that the demand for traditional and smart adaptive façades widely rises as the number and height of tall buildings are incredibly increasing every year. However, further scientific research on this topic could respond to the current limitations and enrich the existing knowledge on the design and application of adaptive façade systems for tall buildings. However, the focus has been on their energy-saving and ventilation applications. However, as highlighted in the previous section, there are opportunities to combine their energy-saving, sustainability-boosting capabilities to also modify building aerodynamics. It is believed that smart adaptive façades with advanced and innovative design can be a promising solution to not only satisfy their traditional design purposes but also provide better aerodynamic performance to ensure building resistance against wind-induced loading.

7. Conclusions

The number of tall buildings is growing worldwide in recent years. The heights or aspect ratios of such buildings have incredibly increased over the past few years, making them more flexible and vulnerable to wind events. Apart from using existing passive and active auxiliary dampers, aerodynamic modification approaches of such slender structures have gained considerable attention among designers and scholars seeking to effectively reduce wind-induced loads and vibration of tall buildings. To this end, a notable number of research projects have been conducted to explore their effects using CFD modeling and wind tunnel experiments. Recent studies confirm that the double-skin façades, usually known as ventilation and energy-saving systems, can improve the aerodynamic performance of tall buildings by increasing surface roughness and providing a porous medium. These two factors change the wind-induced pressure that determines the wind loading and excitations around the building structure. This paper primarily reviews the past studies on the aerodynamic application of double-skin façades and provides a concise summary of available aerodynamic modification approaches that could be used as the first design stage for smart facades. Furthermore, the capabilities within the architectural engineering and envelope design communities for the development of adaptive facades have been highlighted. This paper proposes the opportunity for the integration of these approaches to achieve a smart morphine façade that not only can be used for the purpose of energy savings but also can be utilized to enhance the aerodynamic performance of the building. The significant findings addressed earlier in this paper are summarized below. It should be mentioned that these aerodynamic improvements are observed for specific cases and conditions, and they may not have a similar impact on tall building aerodynamics in other situations.

- The most common trend is that the closer to circularity, the smaller the force coefficients achieved. The ABL conditions reflect more realistic results since they mimic actual atmospheric boundary conditions, even though higher loads (absolute values) have been reported with ABL testing.
- The combined models with multiple modifications generally exhibited better aerodynamic performance than single modification cases. The square shape had the largest normal peak stress among all models. The largest normal peak stress of models with multiple modifications was generally smaller than for the single modification models. According to the results, the building with corner-cut, tapering, and 360° helical shape had the smallest peak stress. Among the single modifications, the setback model had the lowest peak stress.
- The drag coefficient could be reduced by up to 40 % with rounded corners, and among all the studied models rounded-corner model had the lowest absolute pressure coefficients for the front and back faces. In contrast, the sharp-corners model exhibited the highest pressure coefficients. According to the results, the rounded-corner shape was reported as the best performing modification among the minor changes tested. Small corner cuts and recessions were very effective in reducing instability. In contrast, larger corner-cuts and recessions promoted instability at low velocity to decrease the onset of critical wind speed for galloping. While corner modification has little effect on wind-induced vibration, it could significantly reduce wind response at higher velocity. Comparing the results obtained for minor and major changes proves that the models with major changes perform better. It was found that the separated shear layer tends to reattach to the windward face of the building and decreases excitation as the angle of attack increased.
- The highest drag reduction of a twisted building compared to a straight building is about 6%. Another advantage of twisting is changing the Strouhal number with height resulting from variation in the vortex shedding frequency. While twist can be an excellent choice for avoiding undesirable across-wind force from vortex shedding, the numerical simulations reflected nearly insignificant drag reduction for twisted towers. However, the twisting approach tends to narrow down the drag force change as wind direction varies.
- The results indicate that tapered and setback models exhibit the best aerodynamic performance for the triangular case due to having the lowest drag coefficients. The tapered case exhibited a 24 % reduction in drag coefficient compared to the basic model, while the setback model exhibited a reduction of approximately 21 %. On the other hand, the helical modification increased the drag coefficient to 1, while the drag coefficient of the basic model was 0.79 under the same conditions.
- In general, surface roughness, such as that from window sashes, wall textures, and balconies, reduces the peak pressures leading to mitigate the drag force. The idea that roughness could efficiently decrease wind load on buildings has led to more recent studies considering the addition of attachments represented by balconies in real conditions to provide surface roughness and reduce aerodynamic loads on tall buildings. Although balcony design has other applications and architectural purposes, it may alleviate the mean or fluctuating wind components by changing the wind-induced pressure around the building due to increasing the surface roughness. The addition of roughness to the façade also decreased vorticity close to the upwind corner. Another potential approach is to motivate the use of facades that resemble the effect of balconies on the building by adding roughness to a building surface to mitigate wind loading by modifying the flow characteristics.
- The review indicated that the vertical opening in the DSFs had only a negligible effect on wind-induced response mitigation in the along-wind direction, but a significant impact was observed in the across-wind direction. Pressure-test results proved that the façade with no opening had the largest fluctuating pressure on the side faces.
- It was found that a DSF without opening results in an increase in the mean suction pressure and fluctuating pressure on the leeward face and both sides. Conversely, the pressure was reduced on the leeward face and sides for DSFs with the opening(s). According to the results for DSFs, the along- and across-wind responses and the torsional excitation were considerably reduced by attaching the DSFs with vertical openings. It is concluded that DSFs with configurations with openings could effectively mitigate wind loading.
- A double-skin façade system could mitigate positive and negative peak pressures of the inner glazed façade by up to 40 %. Moreover, the DSF system can function as a filter for a pressure signal that positively influenced the mean and standard deviations. Furthermore, the pressure coefficient inside a DSF's gap was always reported negative for all wind directions.
- Limited research on the cactus-shaped surfaces shows that they could significantly alleviate the mean and fluctuating drag force by up to 20 % on tall buildings because of modifying the flow mechanism. This innovative bio-inspired design combined with DSFs could considerably modify the wind-induced loads and responses of tall buildings. They could also lead to requiring less material and lowering construction costs for tall buildings while providing an interesting artistic shape. Considering the limited research on this topic, further investigations focusing on their applications for double-skin façade systems are necessary to explore their impacts and understand flow mechanisms.

- "Adaptive facades" are multi-objective, high-performance envelopes that respond mechanically or chemically to external climate dynamics to meet inside load requirements (cooling, heating, lighting, or ventilation) and occupants' needs. There has been an extensive increase in the use of adaptive facades for energy saving, sustainability, and architectural purposes. These components continuously and proactively react to outdoor and indoor environmental conditions and facilitate the exploitation of renewable and low-energy sources. The current rise in using adaptive or dynamic facades for energy savings provides an opportunity to further use these facades to mitigate wind effects.

There has been limited research on the flow interactions induced by multiple adjacent tall buildings in downtown areas. As more tall buildings are constructed to meet future urbanization and urban sustainability demands, these interactions and wind-induced loads will generally become more important. Thus, future investigations require considering the effect of surrounding high-rise buildings to ensure the sustainability of developing structures against wind loading. Experiments on DSF imply that their aerodynamic use can be integrated with their other applications through efficient design, and promising results encourage scholars to perform new research studies on designing smart double-skin façades to push the limits further and alleviate wind-loading issues of such structures. Adaptive façades and other applications could improve motion-control performance, and bio-inspired designs inspired by natural structures such as cactus shapes can be combined with designing DSFs to take advantage of natural phenomena in enhancing building performance. Knowing more about aerodynamic modifications would help to build more effective double-skin façades. To this end, a series of benchmark studies must be conducted to provide enough knowledge about the impacts of influential parameters and their combinations, such as wind direction, wind speed, major and minor shape modification, surface roughness, and other surrounding structures. Although there have been only limited studies on the aerodynamics of DSFs, they mostly deal with pressure distribution and load measurement. More experimental and CFD investigations are essential to fully understand the flow mechanism of DSFs and explore the design limitations and advantages of such systems. To this end, three-dimensional CFD simulations would be an excellent choice to visualize flow behavior passing openings and around tall buildings. Such fundamental investigations could improve the DSF's design to efficiently control the flow for mitigating aerodynamic loads and wind-induced response. It is also believed that the promising recent advancements in artificial intelligence and adaptive façades open up opportunities to develop smart morphing facades (i.e., Smorphacades) that can revolutionize aerodynamic shape modification of tall buildings to ensure their resilience to moderate to extreme wind loads. Furthermore, special attention requires to study the application of smart materials in developing adaptive façades.

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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