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Aerodynamics of closely spaced buildings: with application to linked buildings

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Abstract: This paper investigates inter-building and intra-building aerodynamic correlations of linked buildings (LBs, i.e., adjacent tall buildings structurally connected by links such as skybridges, skypools and skygardens). Spatiotemporal wind pressure data on a typical LB setup with different gap distances are used to examine inter-building aerodynamic correlation, which is presented in terms of the correlation coefficients between local wind force components and between generalized force components of the two LBs. The along-wind inter-building correlation coefficient is found to decrease for wind direction $\alpha = 0^\circ$ and increase for $\alpha = 90^\circ$ with increasing gap distance, whereas variation of cross-wind inter-building correlation is complicated. In addition, it is illustrated that the wind-induced response of the LBs usually relates positively to the correlation coefficient between the generalized force components of the two buildings in the associated unlinked case. Intra-building aerodynamic correlation of the LBs is examined using correlation coefficients and trajectories, and then compared with those of an isolated building. Results show that intra-building aerodynamic correlations differ considerably, especially between along-wind and torsional force components. However, although intra-building aerodynamic correlation is significant, its effect on the wind-induced responses of LBs is found to be relatively small. It may even be overshadowed by the effects of link-induced structural coupling.

Keyword: inter-building correlation; intra-building force correlation; wind-induced response; linked buildings; tall buildings

1. Introduction

There is a growing trend to link buildings in close proximity using horizontal structures such as skybridges, skypools and skygardens. Notable examples of linked buildings (LBs) are Singapore's Marina Bay Sands and Japan's Umeda Sky Building. LBs often stand close to each other and have great heights, so wind-resistance is one of primary concerns in design practice, particularly in typhoon-prone areas. When two buildings are separate, they vibrate independently in response to wind excitation, whereas when there are structural links between them, the links can couple the motions of the connected buildings by transferring internal forces (i.e., structural coupling) and the two connected buildings work as a whole to resist external wind forces. As a result, wind forces on all the connected buildings should be taken into consideration simultaneously to accurately reflect the true nature of wind-excited LBs and calculate the resulting structural responses (Xie and Irwin, 2001; Lim and Bienkiewicz, 2007; Lim, 2009). It is evident that the correlation between wind forces applying on the LBs (i.e., aerodynamic coupling) plays an important role in the result of the simultaneous consideration.

In fact, the link-induced structural coupling has been researched extensively. For instance, Lim's group investigated the effect of the link-induced structural coupling on frequencies of twin buildings connected by a link, using a simplified six-degree-of-freedom model (Lim, 2009; Lim et al., 2011; Lim and Bienkiewicz, 2014). The effects of the structural coupling on the modal properties and wind-induced responses of LBs have also been examined

systematically in a number of previous studies (Tse and Song, 2013a, b, c; Song and Tse, 2014; Tse and Song, 2015). It has been shown that LBs oscillate in one of the two modes in each direction: the in-phase mode (i.e., two towers vibrating along the same direction) and the out-of-phase mode (i.e., two towers vibrating in opposite directions). Further, stiffness of the structural link has been shown to have no effect on the in-phase mode, whilst increases the out-of-phase mode's frequency, hence reducing the associated modal responses.

Because LBs usually stand very close to each other, wind forces on one of the buildings will interact with wind forces on the other building. Consequently, both the magnitude and correlation of wind forces on LBs could differ from those for a single isolated building. The effects of the presence of adjacent building(s) on the wind force magnitude and wind-induced response of a principal building have already been studied extensively in terms of the interference effect (McLaren et al., 1971; Lee and Fowler, 1975; Bailey and Kwok, 1985; Taniike, 1991; Taniike, 1992; Yahyai et al., 1992; Zhang et al., 1994; Khanduri et al., 1998; Sakamoto and Haniu, 1988; Taniike and Inaoka, 1988; Thepmongkorn et al., 2002; Xie and Gu, 2007; Lam et al., 2008; Kim et al., 2011; Hui et al., 2013; Mara et al., 2014). However, the layout in most of these studies had one building act as the principal—only that principal building would be equipped with instrumentation to measure wind forces—and all adjacent buildings as mere dummy blocks, placed there to produce interference. In other words, very few studies examined aerodynamic correlations of LBs; the ones that did (Kareem, 1982; Tamura et al., 2000; 2001; 2008; 2014) looked at aerodynamic correlations between wind

force components on a single isolated building.

As mentioned, when adjacent buildings are not structurally linked, they vibrate independently in response to wind excitation. In this case there is no need to consider the correlation in wind force components *between* the buildings (i.e., *inter*-building aerodynamic correlation). However, the wind forces on the connected buildings should be considered simultaneously due to the link-induced structural coupling. This involves summing wind force components of each of the buildings. It is evident that the inter-building aerodynamic correlation plays an important role in the summation. The correlation between wind force components *within* each building (i.e. *intra*-building aerodynamic correlation) is also important because it is related to the combination of the resulting directional structural responses (Thoroddsen et al., 1988; Tamura et al., 2001; Tamura et al., 2008; Tamura et al., 2014). Due to the interaction between wind forces on the LBs, however, the intra-building correlation is likely to be different from that of an isolated building (Kareem, 1987; Khanduri et al., 1998; Kim et al., 2011).

It is important to note that Lim's group simultaneously measured the base overturning moments and torsional moments of two generic building models using a *duel* high-frequency base balance (HFBB) technique (Lim, 2009; Lim et al., 2011; Lim and Bienkiewicz, 2014). The base moments were then used to calculate the aerodynamic correlation between two buildings in a set of cases where gap distance and building orientation varied. The wind-induced response of each case, however, was calculated using the traditional HFBB

based approach that required mode shape correction. Base overturning moments and torque alone may not provide an accurate portrait of the local distribution of aerodynamic characteristics along the height of the building, but they adequately represent the global effects of interference, such as integral loads and the weighted averages of local effects. Lim's group used a generic mode shape expressed by a power function and the associated mode shape correction factors to determine structural responses, but the details on how to determine mode shapes of the LBs were not reported. Previous studies (Tse and Song, 2013a, b, c; Song and Tse, 2014; Tse and Song, 2015) have shown that an LB's mode shapes may differ significantly from those of a standalone building. In some cases, the mode shapes of an LB cannot be fitted by a power function. When that happens, the inherent assumptions about mode shapes and the use of mode shape correction factors may introduce uncertainties to the predicted generalized forces and structural responses (Tschanz and Davenport, 1983; Yip et al., 1998; Zhou and Kareem, 2002; Chen and Kareem, 2005; Lam and Li, 2009; Tse et al., 2009; Huang et al., 2010; Huang et al., 2011; Bernardini et al., 2013), which may affect the reliability of the observations derived from these studies. Nonetheless, these studies offer a comprehensive formulation of LBs and their response under winds.

In light of the preceding comments, the integrated effect of local loads masks any local variations of loads along the height of an LB, which may influence both the intra- and inter-building local force correlations that may not be captured by the HFBB approach, resulting in an inaccurate portrayal of the LB's response. Measuring pressure synchronously

on the building's surface, which maps accurately the distribution of both local and integral loads, may resolve this. This also allows the introduction of a desired mode shape for generalized loading, a flexibility that is not offered by the HFBB approach when the mode shape deviates significantly from the linear. Clearly, there remains the need to investigate both inter- and intra-building aerodynamic correlations using detailed pressure measurements, and to try to understand their effects on the wind-induced response of an LB; such is what motivates this study.

The objective of this study is then to investigate the inter- and intra-building aerodynamic correlations and their effects on the dynamic response of LBs. This study used five LB models, each with different designed gap distance. Fluctuating wind pressures on each face of the buildings in each model were simultaneously measured in the wind tunnel first. Then, the inter- and intra-building aerodynamic correlations were examined separately in detail. Their effects on the wind-induced response of LBs were investigated and generalized. The main findings are summarized in the concluding section.

2. Experimental measurement

The tests were carried out in the boundary layer wind tunnel of the CLP Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology. Five cases of LBs with different gap distances (S) were considered. In each case, two buildings were linked at the top and had identical dimensions, as shown in Fig. 1.

Fig. 1. Setup of two square buildings, wind direction, and coordinate

The prototype was a pair of square-cylinder buildings, 160 m tall and $30 \text{ m} \times 30 \text{ m}$ in plan in a way typical of LBs. The separation between the buildings, or the gap distance S , ranged between 10 m and 45 m, which corresponded to $1/3$ and $3/2$ of the building breadth B . The specific gap distances and S/B ratios for all test cases are listed in Table 1. This paper considers the structural link to be relatively thin, with a thickness of only two to three floors at most, such as was in the scenario studied by Song and Tse (2014). Previous studies have indicated that a thin structural link has negligible effect on wind flow around the two buildings, so in this study the physical model of the link was omitted in the wind tunnel test. The case of the associated isolated building, on the other hand, was tested and has been included as case 0 in Table 1 for comparison. The scale between model and prototype was 1:400. Fig. 2 shows case 4 ($S/B = 1$) undergoing tests in the wind tunnel.

Table 1. Gap distance (S) and gap-to-breadth ratio (S/B) of all test cases

Gap distance (S) and ratio (S/B)		Cases					
		case 0	case 1	case 2	case 3	case 4	case 5
S	prototype scale (m)	-	10	15	20	30	45
	model scale (mm)	-	25	37.5	50	75	112.5
	S/B	-	1/3	1/2	2/3	1	3/2

Fig. 2. Model (case 4, $S/B = 1$) in the wind tunnel

The wind used in the tests had a mean speed, measured at the top of the LBs, of 42.8 m/s in prototype scale and a longitudinal turbulence intensity of 13.9%. The approaching flow was simulated as natural wind over an open terrain; its horizontal mean wind velocity profile had a power law exponent of 0.2. Both mean wind speed and turbulence intensity profiles

were calibrated and the calibration results are shown in Fig. 3.

Fig. 3. Simulated mean wind speed and turbulence intensity profiles

A synchronous multi-pressure measuring system (SMPMS) with 9 levels of pressure taps on each face of the buildings in the model and 5 taps per level (360 taps in total) was used to measure pressure in each case. After wind pressure data on all faces were synchronously collected, the time histories of the local wind forces pertaining to each floor, base forces, two base overturning moments, and the base torque were determined by integrating over the associated wind pressure field. The tested wind speed in the wind tunnel was approximately 15.9 m/s at the top of the model, with a resultant Reynolds number of 7.9×10^4 , which passed the required value of 5×10^4 (AWES-QAM-1-2001). The period of the pressure measurement was about 60s (e.g. equivalent to approximately 2 hours in prototype scale). The sampling frequency in the wind tunnel was 500 Hz. All measurements from the wind tunnel were scaled similarly from model to prototype, and results of the analysis are shown in prototype scale in the following sections.

3. Inter-building aerodynamic correlation

Our previous study has indicated the two critical wind directions ($\alpha = 0^\circ$ and 90°) over the 360° azimuth where the LBs' structural responses are largest. In this section, we mainly focus on results for these two directions.

3.1 Fluctuating aerodynamic forces

We first look at the fluctuating component of aerodynamic forces on the LBs to first understand the general mechanism of wind flow around the system, and second, to validate the accuracy of the acquired data by comparing them with previous research. Two non-dimensional force coefficients, $C_{FD,q}$ (the along-wind force coefficient) and $C_{FL,q}$ (the cross-wind force coefficient) are examined, which are defined as

$$C_{FD,q} = \frac{F_{D,q}}{\frac{1}{2} \rho_{air} V_H^2 B H}, \quad C_{FL,q} = \frac{F_{L,q}}{\frac{1}{2} \rho_{air} V_H^2 B H} \quad (1)$$

where $F_{D,q}$ and $F_{L,q}$ are the respective along-wind and cross-wind base forces on Tower q ($q = 1$ and 2); ρ_{air} represent the air density; and V_H is the wind velocity at the top of the building.

The fluctuating components of $C_{FD,q}$ and $C_{FL,q}$ are investigated in terms of their standard deviations (σ_{CFD} and σ_{CFL}).

Fluctuating components of C_{FD} and C_{FL} for $\alpha = 0^\circ$

When $\alpha = 0^\circ$, the oncoming wind is normal to the windward faces of the LBs and the two buildings are in a side-by-side symmetric arrangement (refer to Fig. 1). In this arrangement, the statistical characteristics of the aerodynamic forces on both buildings are identical in

theory. Hence, discussing results from only one of the buildings will suffice. We choose the building on the right (i.e., Tower 2).

The values of σ_{CFD} and σ_{CFL} for the five LB cases and their isolated building counterpart case are shown in Fig. 4.

Fig. 4 Variation of σ_{CFD} and σ_{CFL} with S/B for $\alpha = 0^\circ$

It can be observed that within the tested range of gap distance ratio S/B , σ_{CFD} is not very sensitive to S/B , suggesting understandably that gap distance does not have a significant influence on the fluctuating component of the along-wind force coefficient C_{FD} . This is reasonable, because for $\alpha = 0^\circ$, the along-wind force mostly comes from pressure fluctuations on the windward face and these fluctuations largely follow the turbulence in the approaching flow, which is hardly affected by the gap. A minor trough for σ_{CFD} is observed at $S/B = 0.5$, which has also been reported by Sakamoto and Haniu (1988) for a similar gap ratio. This phenomenon can be explained by gap flow. When S/B is small (e.g., 0.33), gap flow is very weak, so the two buildings largely behave like a single bluff body with a side ratio of 1/2. Increasing S/B to 0.5 facilitates gap flow. The flow now behaves like a high speed jet flow and

204 bleeds into the separate regions behind the leeward faces, distorting vortex formations there,
205 hence decreasing suction on the buildings' rear faces (Bearman, 1967; Sakamoto and Haniu,
206 1988). Further increasing gap distance, however, weakens gap flow. The flow then starts to
207 roll up gradually from the windward corners to the rear region around the leeward side,
208 increasing the along-wind force. Furthermore, values of σ_{CFD} in all five LB cases do not
209 deviate considerably from that for an isolated building, because in all cases, turbulence in the
210 approaching wind is the major contributing factor to the fluctuating component of the
211 along-wind force coefficient C_{FD} . This has been confirmed by Sakamoto and Haniu (1988),
212 Taniike (1992), and Lam et al. (2008).

213 Variations in σ_{CFL} of the five LB cases, on the other hand, differ significantly from
214 variations in σ_{CFD} . Within the tested range of S/B , values of σ_{CFL} increase with S/B except when
215 $S/B = 0.5$ where σ_{CFL} is the minimum value. This trend agrees with that reported by Sakamoto
216 and Haniu (1988), but with slightly different magnitudes, because the models' aspect ratios
217 and the turbulence intensity of the site category are different between the studies. When S/B is
218 small (< 0.5), gap flow is very weak and the separated shear layers from the windward corners
219 of the outer side of the two buildings interact with each other and roll up to produce a
220 large-scale vortex. When S/B is increased to 0.5, the power spectral density (PSD) of the
221 associated cross-wind base moment is relatively small, as is shown in Fig. 5 and has been
222 similarly demonstrated by Sakamoto and Haniu (1988). The reason for this is that the
223 increased gap flow in this case can suppress periodic vortex, like a base bleed. When the ratio

224 S/B becomes larger than 0.5, σ_{CFL} increases significantly, as a result of the asymmetric flow
 225 that produces two distinct vortex streets from both the unbiased outer faces and the biased
 226 inner faces. For the same reason, the peak of the PSD shown in Fig. 5 gradually approaches
 227 that of the isolated building when S/B increases from 0.5 to 1.5. It can be expected, then, that
 228 when S/B becomes sufficiently large (e.g., $S/B \geq 1.5$), each building will have its own vortex
 229 shedding, and σ_{CFL} approaches that of an isolated building.

230
 231 **Fig. 5.** PSD of cross-wind base moment for $\alpha = 0^\circ$

232 *Fluctuating components of C_{FD} and C_{FL} for $\alpha = 90^\circ$*

233 At $\alpha = 90^\circ$, the two buildings are in a tandem arrangement and the wind forces on the two
 234 buildings are markedly different. In view of this fact, the force coefficients of both buildings
 235 are shown in Fig. 6 for this wind direction

Fig. 6. Variation of σ_{CFD} and σ_{CFL} with S/B for $\alpha = 90^\circ$

It was reported by Sakamoto et al. (1987) and Sakamoto and Haniu (1988) that the fluctuating components of the along-wind force coefficient C_{FD1} and the cross-wind force coefficient C_{FL1} of the upstream building are not significantly affected by gap distance. This phenomenon can be also observed in Fig. 6 and Fig. 7a, which in part validates the accuracy of the measurement in this study. The minor decrease in C_{FD1} and C_{FL1} when $S/B > 0.67$ is due to the fact that with an increase of S/B , parts of the separated shear layers from the two windward corners of the upstream building start to intermittently bleed into the gap. This may cancel some aerodynamic forces on the windward side of the upstream building, thus affecting vortex shedding (Sakamoto et al, 1987; Sakamoto and Haniu, 1988; Khanduri et al, 1998). As seen in Fig. 7a and c, when frequency is high, the PSD is relatively small for cases with large S/B .

Fig. 6 shows that the standard deviations of the two force coefficients of the downstream building (i.e., C_{FD2} and C_{FL2}) are much smaller than those of the upstream building, especially for C_{FD2} . This clearly indicates a severe shielding effect from the upstream building. The shielding effect is also observable in Fig. 7b and d. As can be seen, in most of the frequency range, the PSD of the downstream building is much smaller than that for the isolated building. Furthermore, Fig. 6 shows that the standard deviation of C_{FL2} increases slightly with S/B , but

259 the standard deviation of C_{FD2} is nearly constant within the observed range of S/B . The slight
 260 increase in C_{FL2} can be explained by vortex shedding from the two windward corners of the
 261 downstream building. As S/B increases, the cross-wind force on the downstream building is
 262 no longer produced entirely by the reattachment of the separation shear layers that are
 263 initiated from the two windward corners of the upstream building. Parts of the separation
 264 shear layers of the upstream building intrude into the gap region and then flow downward
 265 through the two windward corners of the downstream building, leading to the formation of
 266 vortex shedding in the downstream building. As a result, both the cross-wind PSD and vortex
 267 shedding frequency of the downstream building increase with S/B , as shown in Fig. 7d.

Fig. 7. PSD of base moment for $\alpha = 90^\circ$: (a) along-wind base moment of Tower 1; (b)

along-wind base moment of Tower 2; (c) cross-wind base moment of Tower 1; (d) cross-wind
base moment of Tower 2;

3.2 Inter-building correlation between local wind force components

We now proceed with inter-building correlation. Inter-building aerodynamic correlation is examined in terms of the correlation coefficient between local wind force components, which is defined as

$$\rho_{Fn1,Fn2} = \frac{E\left[\left(F_{n,1}(z,t) - \mu_{Fn,1}\right)\left(F_{n,2}(z,t) - \mu_{Fn,2}\right)\right]}{\sigma_{Fn,1}\sigma_{Fn,2}} \quad (2)$$

where $F_{n,q}(z, t)$ are time histories of the force components on tower q at elevation z , in which $n = D$ or L , denoting the along-wind and cross-wind force, respectively; $\mu_{Fn,q}$ and $\sigma_{Fn,q}$ are the mean value and standard deviation of force component $F_{n,q}$; $E(*)$ is the expectation operator to calculate the average value of variable $*$; and $\rho_{Fn1,Fn2}$ is the associated correlation coefficient.

Inter-building correlation for $\alpha = 0^\circ$

Fig. 8 shows the correlation coefficients between the local wind forces on the two buildings for $\alpha = 0^\circ$. It can be observed from Fig. 8a that at most levels, the correlation coefficients of the along-wind forces decrease with increasing S/B . This decreasing trend can be explained by the fact that along-wind forces are mainly attributed to the approaching wind, the correlation of which decays with an increase in the lateral separation distance. Therefore, the correlation between along-wind forces on the buildings is expected to become relatively weak when S/B becomes very large (> 1.5) for $\alpha = 0^\circ$. At high levels ($h/H > 0.8$), however, wind forces for $S/B = 0.5$ and 0.67 do not always follow this trend. This unusual variation may be attributed to the complicated 3D flow (tip flow) around the top of the buildings. When S/B increases from 0.5 to 0.67 , the 3D flow may increase the correlation between the suction forces on the two leeward faces, to some extent delaying the decrease of the correlation between the forces on the two windward faces, resulting in the correlation coefficients not decreasing significantly from $S/B = 0.5$ to 0.67 .

Fig. 8. Correlation coefficients between two wind force components on Tower 1 and Tower 2 at the same level for $\alpha = 0^\circ$: (a) along-wind; (b) cross-wind

Unlike the inter-building correlation between along-wind forces, the correlation between cross-wind forces does not continuously decrease or increase with gap distance, as shown in Fig. 8b. In the range $0.3 < h/H < 0.9$, the absolute values of the correlation coefficients increase with S/B from 0.33 to 0.50, whereas increasing S/B further from 0.5 to 1.5 leads to a gradual decrease in the absolute value of the correlation coefficients. The increase in the correlation coefficient can be explained by an increased gap flow—accelerated wind passing through the gap may increase the correlation between the two suction forces on the two inner faces of the buildings. The decrease, on the other hand, is due to the fact that increases in S/B above 0.5 can gradually allow the shear layers from the two inner edges to roll up into the rear region of the two buildings through the gap, interrupting the original negative correlation between cross-wind forces. In addition, within the range $0.3 < h/H < 0.9$, almost all

correlation coefficients are negative, indicating that vortex shedding is dominant. At the top and bottom (i.e., $h/H > 0.9$ and $h/H < 0.3$), in contrast, the correlation coefficients for cross-wind forces are positive. This is because the flow around the top is complicated, which can be attributed to downwash from the tip flow that disrupts the organized structure of wake fluctuations, resulting in the positive, albeit slight, correlation. Similar trends were noted by Ayoub and Karamcheti (1982) and Kareem et al. (1989). Consequently, the negative correlation around the top of the building is weak, becoming positive even. Similarly, vortex shedding around the bottom region is not fully formed, so cross-wind forces at the bottom of the two buildings are slightly positively correlated (also observed in Kareem et al. 1989).

In addition to the correlation coefficient, the inter-building correlation function R for time lag τ is also calculated for local wind forces at a representative height of $0.8H$, as shown in Figs. 9 and 10. It can be observed in Fig. 9 that along wind forces have their largest values at zero time lag in all cases. The correlation decays significantly as time lag τ increases. Further, for most of the time lags, the value of the associated correlation function decreases with increasing gap-to-breadth ratio S/B , which agrees with the trend shown in Fig. 8a. However, the correlation function for the cross-wind forces shows a rather complicated pattern. As can be seen from Fig. 10, the largest correlation does not occur at zero time lag, nor does the correlation monotonically decay with time lag τ . For instance, the largest correlation appears at $\tau = -2.4\text{s}$ for $S/B = 0.5$ and $\tau = 6.6\text{s}$ for $S/B = 0.67$. This is in fact what we have expected, because although perfect vortex shedding does not develop because of the

gap between the buildings, an obvious peak can still be found from the PSD of the cross-wind
base moment of the LB cases shown in Fig. 5. In other words, parts of the vortices continue
to be shed alternately from the two buildings, and cross-wind forces on the buildings are
somewhat out of phase. For the same reason, the correlation function R is observed to have an
embedded periodicity, albeit a rather weak one. As a result, the correlation function between
cross-wind forces shows the largest absolute value at a certain non-zero, rather than zero, time
lag.

Fig. 9. Inter-building correlation function between along-wind forces at $0.8H$ for $\alpha = 0^\circ$ (a):

$S/B = 0.33$; (b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$

Fig. 10. Inter-building correlation function between cross-wind forces at $0.8H$ for $\alpha = 0^\circ$

(a): $S/B = 0.33$; (b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$

Inter-building correlation for $\alpha = 90^\circ$

The inter-building correlation for $\alpha = 90^\circ$ is likely to differ significantly from that for $\alpha = 0^\circ$ because the buildings are in a different arrangement, so it is necessary to take a closer look at it, which is shown in Fig. 11.

Fig. 11 Correlation coefficients between two same wind force components at the same level

for $\alpha = 90^\circ$: (a) along-wind; (b) cross-wind

Fig. 11a shows the correlation coefficients between along-wind forces on the twin towers for $\alpha = 90^\circ$. As can be seen, the correlation coefficients at most elevations are negative, which

is distinctly different from those for $\alpha = 0^\circ$. The negative correlation decreases monotonically with increasing S/B . When $S/B = 0.33$, the flow around the two buildings almost behaves like that around an isolated building with a larger side ratio. In this case, the along-wind force of the downstream building Tower 2 is minimal, resulting in a large negative correlation between the two along-wind forces. Increasing gap distance gradually decreases this negative correlation, as part of the windward face of the downstream building can be directly impacted by the wind flow penetrating into the gap between the two buildings. This correlation can therefore be expected to become positive when gap distance is large enough, because when the gap is wide, the downstream building may be outside the upstream building's region of wake flow, and along-wind forces on both buildings are mainly attributed to the approaching flow.

Fig. 11b shows the correlation coefficients between cross-wind forces for $\alpha = 90^\circ$. Similar to that shown in Fig. 8b for $\alpha = 0^\circ$, the coefficients here do not show monotonic variations with increasing S/B . As can be seen, when $S/B \leq 1$, the negative correlation increases slightly with S/B , whereas the negative correlation reduces significantly when S/B increases from 1.0 to 1.5. It was reported in Sakamoto and Haniu (1988) that when $S/B < 1$, the separated shear layers from the side faces of the upstream building could attach to the side faces of the downstream building, resulting in a relatively large negative correlation between cross-wind forces because of phase shift. When $S/B > 1$, part of the separated shear layers from the upstream building gradually rolls up into the gap between the two buildings, which

368 may affect the correlation.

369 The inter-building correlation function for $\alpha = 90^\circ$ is shown in Figs. 12 and 13. It can be
370 observed from Fig. 12 that all values of the coherence functions of the five cases are negative
371 especially when S/B is small, indicating a negative correlation between along-wind forces on
372 the buildings. In addition, for each case, the correlation coefficient at zero time lag has the
373 largest absolute value and the value decays with increasing time lag τ . This decay, however, is
374 not present in the correlation function between cross-wind forces. As can be seen in Fig. 13,
375 in addition to a clear trough around zero time lag there is a peak. This indicates that although
376 at zero time lag the correlation function (or correlation coefficient) is usually negative for
377 cross-wind aerodynamic correlation, the cross-wind force on the downstream building is
378 positively correlated to the cross-wind force on the upstream building before a certain time.
379 This may be explained by the fact that after that certain time, the separated shear layers from
380 the upstream building will reattach itself to the side faces of downstream building.

Fig. 12 Inter-building correlation function between along-wind forces at $0.8H$ for $\alpha = 90^\circ$: (a)

$S/B = 0.33$; (b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$

Fig. 13 Inter-building correlation function between cross-wind forces at $0.8H$ for $\alpha = 90^\circ$: (a)

$S/B = 0.33$; (b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$

3.3 Effect of correlation on the wind-induced responses of LBs

Fig. 14. Structural system of the LB in case 2 ($S/B = 0.5$)

The effects that inter-building aerodynamic correlation has on the wind-induced responses of LBs are examined in this section using the same five LB cases from section 2. To highlight the effects of inter-building correlation, modal properties of the five LB cases are assumed to be identical to those in case 2 ($S/B = 0.5$). This way, structural coupling due to the link is equal in all five cases and the difference between the resulting responses is then attributable only to aerodynamic forces. The structural system for case 2, which was also employed in our previous study (Song and Tse 2014), is shown in Fig. 14 for easy reference. The first three frequencies of the system are 0.239 Hz (x), 0.239 Hz (y), and 0.3 Hz (θ). A damping ratio of 2% has been set for all modes.

3.3.1 Correlation between generalized force components of two towers

As mentioned in the introduction, because of link-induced structural coupling, connected buildings behave as a whole to resist external wind forces. Therefore, wind forces on both buildings should be considered simultaneously to precisely determine their wind-induced responses. For example, the j -th generalized force F_j^* on the overall LB system is the summation of generalized force components from both towers, i.e.,

$$\begin{aligned} F_j^*(t) &= F_{j,tower1}^*(t) + F_{j,tower2}^*(t) \\ &= \sum_{i=1}^m F_{tower1}(z_i, t) \Phi_{tower1,j}(z_i) + \sum_{i=1}^m F_{tower2}(z_i, t) \Phi_{tower2,j}(z_i) \end{aligned} \quad (3)$$

413 where F_{tower1} and F_{tower2} are wind forces on Tower 1 and Tower 2, respectively; $\Phi_{tower1,j}$ and
 414 $\Phi_{tower2,j}$ are the j -th mode shape components of Tower 1 and Tower 2, respectively; and $F_{j,tower1}^*$
 415 and $F_{j,tower2}^*$ are the generalized wind force components of Tower 1 and Tower 2,
 416 respectively.

417 Clearly, inter-building correlation between the generalized force components of the two
 418 towers (i.e., $F_{j,tower1}^*$ and $F_{j,tower2}^*$) implicitly presents in Eq. 3. The correlation plays an
 419 important role in the summation and in determining the overall wind-induced responses. More
 420 specifically, when the mode shape components are identical (i.e., $\Phi_{tower1,j} = \Phi_{tower2,j}$), if the
 421 correlation coefficient between $F_{j,tower1}^*$ and $F_{j,tower2}^*$ is significant, the resulting generalized
 422 force F_j^* will be large. However, if the correlation coefficient is insignificant, or even negative,
 423 the resulting generalized force F_j^* will be relatively small. This section will investigate the
 424 inter-building correlation between the generalized force components on the towers as a global
 425 indicator for the correlation.

426 Fig. 15 shows the inter-building correlation coefficients ρ_{F^*in} between the first in-phase
 427 (i.e., two towers synchronously vibrating along the same direction) generalized force
 428 components of the two towers for the two critical wind directions. As can be seen, the
 429 variations in the correlation coefficient are very similar to those shown in Figs. 8 and 11. For
 430 instance, the correlation coefficient ρ_{F^*in} between the along-wind forces for $\alpha = 0^\circ$ decreases
 431 gradually as gap distance increases, because the correlation between along-wind forces on the
 432 two towers (i.e., $F_{tower1}(z, t)$ and $F_{tower2}(z, t)$) decays with increasing gap distance. Additionally,

the correlation coefficient ρ_{F*in} between along-wind forces for $\alpha = 90^\circ$ increases gradually with gap distance, which agrees very well with what is shown in Fig. 11a. However, the correlation coefficient ρ_{F*in} between cross-wind forces for the two wind directions does not vary monotonically with S/B , because of the relatively complicated mechanism of cross-wind forces.

Fig. 15. Correlation coefficient ρ_{F*in} for all LB cases: (a) $\alpha = 0^\circ$; and (b) $\alpha = 90^\circ$

3.3.2 Relationship between the correlation and proportion of generalized force component

As mentioned in the introduction, previous research (Lim, et al., 2011; Song and Tse, 2014) has indicated that there are two main types of mode shapes for LBs: the in-phase and out-of-phase modes. Also has been shown is that link stiffness has no effect on the frequency

of the in-phase mode, whilst increases the frequency of the out-of-phase mode. This reduces the out-of-phase modal responses, because within the range of frequencies for common tall buildings, wind force energy drops significantly with increasing frequency. Therefore, the proportion of the out-of-phase generalized force component in the buildings without a link (i.e., the unlinked case) plays an important role in reducing the total response of the associated LB system. This is because, if the proportion is relatively large, the response has great potential to be reduced in the associated LB system, but if the proportion is small, the response in the LB will not be reduced significantly, regardless of link stiffness. To quantify the proportion, a ratio $r_{out/in}$ is introduced and defined as

$$r_{out/in} = \frac{\sigma_{F^*out}}{\sigma_{F^*in}} \quad (4)$$

where σ_{F^*in} is the standard deviation of the first in-phase generalized force in the associated unlinked case and σ_{F^*out} is that of the first out-of-phase generalized force.

The relationship between the correlation coefficient ρ_{F^*in} and ratio $r_{out/in}$ for $\alpha = 0^\circ$ is shown in Fig. 16. It is evident that for both along-wind and cross-wind forces, larger values of correlation coefficient result in smaller values of $r_{out/in}$. This is because when ρ_{F^*in} is considerable (e.g., ρ_{F^*in} for the along-wind generalized forces when $S/B = 0.33$), the resulting in-phase generalized force component (i.e., the denominator in Eq. 4) is relatively large. Furthermore, a large ρ_{F^*in} will result in a small out-of-phase generalized force component (i.e., the numerator in Eq. 4), on account of the fact that in the out-of-phase mode the mode shapes of the two towers are opposite of each other. Consequently, these two aspects cause large ρ_{F^*in}

to have a small $r_{out/in}$. Additionally, because values of ρ_{F*in} for along-wind forces are much larger than those for cross-wind forces, values of $r_{out/in}$ for along-wind forces are much smaller than those for cross-wind forces. This suggests that in the associated LB system, cross-wind response has higher potential to be reduced than along-wind response.

Fig. 16 Relationship between correlation coefficient ρ_{F*in} and ratio $r_{out/in}$ for $\alpha = 0^\circ$

In theory, because of symmetry, the statistical characteristics of the wind forces on the two towers are identical for $\alpha = 0^\circ$. Thus, the ratio $r_{out/in}$ can be simplified as

$$r_{out/in} = \frac{\sigma_{F*out}}{\sigma_{F*in}} = \frac{\sqrt{\sigma_{F*out,tower1}^2 - 2\rho_{F*in}\sigma_{F*out,tower1}\sigma_{F*out,tower2} + \sigma_{F*out,tower2}^2}}{\sqrt{\sigma_{F*in,tower1}^2 + 2\rho_{F*in}\sigma_{F*in,tower1}\sigma_{F*in,tower2} + \sigma_{F*in,tower2}^2}} = \sqrt{\frac{2-2\rho_{F*in}}{2+2\rho_{F*in}}} \quad (5)$$

where $\sigma_{F*in, tower1}$ and $\sigma_{F*in, tower2}$ are the first in-phase generalized force component of Tower 1 and Tower 2, respectively; $\sigma_{F*out, tower1}$ and $\sigma_{F*out, tower2}$ are for the first out-of-phase generalized force components.

The theoretical results shown in Fig. 16 are in good agreement with those obtained from data measured in the wind tunnel, which validates their accuracy. Additionally, the theoretical consideration reinforces the inversely proportional relationship between the correlation coefficient ρ_{F*in} and the associated $r_{out/in}$.

The relationship between the correlation coefficient ρ_{F^*in} and ratio $r_{out/in}$ for $\alpha = 90^\circ$ is shown in Fig. 17. For this wind direction, there is no theoretic expression for the ratio $r_{out/in}$, because wind forces on the two buildings are different. However, it can still be observed from the figure that in general, a case with a large correlation coefficient ρ_{F^*in} has a small ρ_{F^*in} , for the same reason discussed for $\alpha = 0^\circ$.

Fig. 17 Relationship between correlation coefficient ρ_{F^*in} and ratio $r_{out/in}$ for $\alpha = 90^\circ$

3.3.3 Relationship between the correlation and response of LB

Based on the preceding discussion, it has now become very straightforward to investigate how inter-building aerodynamic correlation in the unlinked case affects the response of the associated LB system. In order to quantify the effect, a ratio $r_{response}$ is introduced, which is defined as

$$r_{response} = \frac{\sigma_{acc, link}}{\sigma_{acc, nolinek}} \quad (6)$$

where $\sigma_{acc, link}$ is the standard deviation of the top acceleration response in the case of an LB; $\sigma_{acc, nolinek}$ is that in the associated unlinked case. The modal properties and wind-induced

responses of the LBs are determined by the method reported in Song and Tse (2014).

Fig. 18. Relationship between the inter-building correlation coefficient ρ_{F*in} and the response ratio $r_{response}$ for $\alpha = 0^\circ$

The relationship between the inter-building correlation coefficient ρ_{F*in} and $r_{response}$ for $\alpha = 0^\circ$ is illustrated in Fig. 18. Clearly, for both along-wind and cross-wind responses, $r_{response}$ increases with ρ_{F*in} . This indicates that when ρ_{F*in} is large in the unlinked case, installing a link (even with large stiffness) will not significantly decrease the response. When ρ_{F*in} is small, on the other hand, the response in the associated LB can be reduced significantly. For instance, the value of ρ_{F*in} for along-wind response in $S/B = 0.33$ is large (0.8), so the value of $r_{response}$ is up to 90%, indicating that installing a link has no significant effect on the reduction in the along-wind response for this case. In contrast, the value of ρ_{F*in} for along-wind response in $S/B = 1.50$ is relatively small (0.56), and so the $r_{response}$ is decreased to 70%. This indicates that in this case, the along-wind response in the LB is decreased by 30%, compared

516 to the response in the associated unlinked case. In addition, it can be observed that reduction
517 in cross-wind response is more significant than that in along-wind response, because the
518 correlation coefficient ρ_{F*in} between cross-wind forces is much smaller than that between
519 along-wind forces. All these results clearly emphasize that inter-building correlation plays a
520 significant role in determining the reduction in the response of LBs.

521 For $\alpha = 90^\circ$, the relationship between the inter-building correlation coefficient ρ_{F*in} and
522 $r_{response}$ is illustrated in Fig. 19. As can be seen, a case with a larger ρ_{F*in} usually has a larger
523 along-wind $r_{response}$, which reinforces the validity of the positive relationship between ρ_{F*in} and
524 along-wind $r_{response}$. It should be mentioned, however, that the cross-wind $r_{response}$ is randomly
525 distributed along ρ_{F*in} , which seems to be out of line with the positive relationship. This is
526 because apart from the inter-building aerodynamic correlation, the difference between the
527 magnitudes of aerodynamic forces on the two buildings also plays a role in the response ratio
528 $r_{response}$. For a case in which the standard deviations of the forces on the buildings are almost
529 identical, such as for $\alpha = 0^\circ$, there is almost no force magnitude difference, so the response
530 ratio $r_{response}$ is only determined by inter-building aerodynamic correlation. Hence a positive
531 relationship between ρ_{F*in} and $r_{response}$ is clearly shown. Nevertheless, in a case where wind
532 forces on the two buildings are distinctly difference, such as for $\alpha = 90^\circ$, the response ratio
533 $r_{response}$ is determined by both inter-building aerodynamic correlation and difference in force
534 magnitude. As a result, when $\alpha = 90^\circ$, the variations of cross-wind $r_{response}$ with ρ_{F*in} are
535 complicated than just an increasing trend. However, this does not invalidate the inverse

relationship. The relationship exists, only to be distorted by the mixed effect from the difference between wind forces.

Fig. 19. Relationship between the inter-building correlation coefficient ρ_{F*in} and the response ratio $r_{response}$ for $\alpha = 90^\circ$

4. Intra-building aerodynamic correlation

Intra-building aerodynamic correlation of LBs also warrants some attention because it is related to the combination of resultant directional wind-induced responses (Chen and Huang, 2009; Tamura et al., 2014; Chen, 2015) and the correlation may differ significantly from that for an isolated building. We will examine intra-building aerodynamic correlation and its effect on the resultant responses for $\alpha = 0^\circ$ in this section. Once again, symmetry allows us to focus only on Tower 2 on the right.

4.1 Trajectories of base moment components

The correlation between wind force components is first investigated by examining the trajectories of the base moment coefficients of Tower 2 (i.e., C_{MD} , C_{ML} , and C_{MT}), which are defined as

$$C_{MD} = \frac{M_D}{\frac{1}{2} \rho_{air} V_H^2 B H^2} \quad C_{ML} = \frac{M_L}{\frac{1}{2} \rho_{air} V_H^2 B H^2} \quad C_{MT} = \frac{M_T}{\frac{1}{2} \rho_{air} V_H^2 B^2 H} \quad (7)$$

where M_D , M_L , and M_T are the along-wind base moment, cross-wind base moment, and base torque of Tower 2, respectively. In addition to examining the trajectories for the five LB cases, trajectories for the associated isolated building are also presented for comparison.

The trajectories for the along-wind and cross-wind forces of all cases are shown in Fig. 20. For the single isolated building, the envelope of the trajectory (shown in Fig. 20f) is half-elliptic. This envelope is very similar to that reported in (Tamura et al., 2014), which in part validates the measured data. Unlike the symmetric trajectory for the building in isolation, however, those for the LB cases shown in Fig. 20a to e are negatively inclined, clearly indicating a negative correlation between along-wind and cross-wind forces. The negative correlation can be explained by the pressure contour shown in Fig. 21. Due to channeling effect caused by the inter-building gap, the wind that flows through the gap accelerates. As a result, pressure on the windward faces in the area close to the gap is increased (Fig. 21a and b). Meanwhile, suction on the two inside faces near the windward edges is also enhanced, as shown in Fig. 21c and d. For Tower 2, pressure on its windward face is along the positive direction while suction on the inside face is along the negative direction. This is what causes

the negative correlation between along-wind and cross-wind forces. As channeling becomes relatively small when gap distance is large, the trajectory for $S/B = 1.5$ is no longer inclined significantly and becomes close to that for the isolated building.

Fig. 20. Trajectories for the along-wind and cross-wind base overturning moments for $\alpha = 0^\circ$:

(a) $S/B = 0.33$; (b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$; (f) single

Fig. 21. Contours of mean pressure for $\alpha = 0^\circ$ on (a) windward face of Tower 1; (b) windward face of Tower 2; (c) inside face of Tower 1; and (d) inside face of Tower 2 for case 2

The trajectories of the along-wind and torsional base moment are presented in Fig. 22. The trajectory for the isolated building shows a normal elliptic envelope, almost the same as that reported in Tamura et al. (2014) for a square-cylinder building with a similar aspect ratio. In contrast, the trajectories for the LB cases (Fig. 22a to e) are rather contracted and negatively-inclined, clearly suggesting a strong correlation between along-wind base moment and torque. This is because the distribution of pressure on the windward faces in an LB is usually skewed (as shown in Fig. 21 where the distribution shifts inward), instead of symmetric. In addition to causing along-wind forces, the asymmetrical pressure distribution will bring about torsional forces on the LBs. Therefore, the trajectories (shown in Fig. 21a to e) for the LB cases cluster within a rather narrow zone, though the zone becomes relatively wider when S/B is large, such as when $S/B = 1.5$. Furthermore, the shape of the trajectories for the LBs shows that it is highly probable that maximal along-wind force coincides with maximal torsional force. Therefore, although correlation between along-wind and torsional forces on the isolated building is weak and usually ignored, correlation between the two wind force components on an LB is considerable and cannot be disregarded without careful consideration.

Fig. 22. Trajectories for the along-wind and torsional base moments for $\alpha = 0^\circ$: (a) $S/B = 0.33$;
(b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$; (f) single

Fig. 23. Trajectories for the cross-wind and torsional base moments for $\alpha = 0^\circ$: (a) $S/B = 0.33$;
(b) $S/B = 0.50$; (c) $S/B = 0.67$; (d) $S/B = 1.0$; (e) $S/B = 1.5$; (f) single

Trajectories for cross-wind base moment and torsional moment are presented in Fig. 23.

It is usually believed that the cross-wind force and torsional moment on an isolated building

are well correlated, since they are both largely caused by wake dynamics. As a result, the trajectory for the isolated building shown in Fig. 23f is an inclined ellipse rather than a normal one. For the same reason, the trajectories for the LBs also show similar envelopes to that of the isolated building, indicating that correlation between cross-wind and torsional force is similar for an LB and a building in isolation. In addition, gap-to-breadth ratio S/B is observed to have no significant effect on the trajectories.

4.2 Correlation coefficient between wind force components

To show the intra-building correlation quantitatively, the (traditional) correlation coefficient between base overturning and torsional moments of Tower 2 in each case is calculated, as presented in Fig. 24, labeled as *traditional*. In addition, it has been suggested that the correlation coefficient between absolute wind force components is more important for evaluating the largest-largest combination of wind forces (Tamura et al., 2003; 2014). Therefore, the correlation coefficients between absolute base overturning moment and torsion are also calculated and shown in Fig. 24 and are labeled as *absolute*.

Along-wind and cross-wind forces on an isolated building are known to have no correlation with each other, because along-wind force is mainly generated by approaching wind turbulence, whereas the dominant cause of cross-wind force is vortex shedding. Therefore, the traditional correlation coefficient between along-wind and cross-wind forces on an isolated building is very close to zero, as shown in Fig. 16a. However, the corresponding absolute correlation coefficient is relatively large. As previously noted (Tamura et al., 2014),

this is consistent with the half-elliptic envelope shown in Fig. 12f. Although the symmetric envelope leads to a low value of the traditional correlation coefficient, the envelope shows that maximum along-wind force is likely to be accompanied by large cross-wind forces, leading to a relatively large absolute correlation coefficient. For LB cases, the traditional correlation coefficients between along-wind and cross-wind base overturning moments are considerable, much larger than that for the isolated building. Similar negative correlation coefficients were also reported by Lim and Bienkiewicz (2014), but the magnitude of the correlation coefficients are smaller than those shown in Fig. 16a. Additionally, it can be observed that the traditional and absolute correlation coefficients for the LB cases do not show significant differences in magnitude, even though one is negative and the other is positive. This suggests that both traditional and absolute correlation coefficients can be used to quantify the correlation between along-wind and cross-wind forces on the LBs.

Fig. 24. Traditional and absolute correlation coefficient between (a) along-wind and cross-wind moments; (b) along-wind and torsional moments; and (c) cross-wind and torsional moments for $\alpha = 0^\circ$

Fig. 24b shows the correlation coefficients between along-wind and torsional moments for all cases. Correlation between the along-wind force and torsion for the isolated building is shown to be weak (small traditional correlation coefficient), because torsional wind force on a single square building is mainly caused by the wake effects. Also noted is that absolute correlation coefficient for the isolated building is much larger than traditional correlation coefficient. This observation agrees well with the findings in Tamura et al. (2014). For all LB cases, on the other hand, magnitudes of both absolute and traditional correlation coefficients

between along-wind and torsional moments are almost the same, because of the slim and inclined trajectory. Both correlations are further observed to decrease in magnitude with increasing S/B . For instance, the absolute correlation coefficient decreases from 0.80 to 0.44 when S/B increases from 0.33 to 1.5. Nevertheless, the correlation coefficient for $S/B = 1.5$ is still larger than that for the isolated building. All these findings show that along-wind force on an LB is highly correlated with torsional moment. It should be mentioned that the corresponding correlation coefficients reported by Lim and Bienkiewicz (2014) are far smaller than those shown in Fig. 16b, likely because of different wind profiles used (e.g., their profile corresponded to a suburban terrain while this study was conducted in an open terrain with different approaching turbulence intensities) and building aspect ratios (i.e. it is about 8 in their research, and 5.33 in this paper).

As shown in Fig. 23, the trajectories between cross-wind and torsional moments for LBs do not show a considerable difference from the trajectory for the isolated building. In fact, all traditional correlation coefficients between cross-wind and torsional moments for LBs are close to those for the isolated building, as shown in Fig. 24c, as the dominant cause of fluctuations in both cross-wind force and torsional moment is vortex shedding. However, absolute correlation coefficients for all cases are smaller than the traditional ones. In other words, the traditional correlation coefficient between cross-wind and torsional moments may overestimate the correlation for the largest-largest combination (Tamura et al., 2014).

4.3 Effects of intra-building correlation on resultant responses

Although our previous discussion has shown that correlation between the wind force components of an LB is relatively significant, it may not translate into wind-induced responses (Thoroddsen et al., 1988), which should be investigated further. To show the effect of intra-building correlation on the resultant responses, components of the wind-induced responses along three directions (i.e., along-wind, cross-wind, and torsional) are calculated. Two types of resultant responses can be calculated: one which considers the correlation, and one that does not. The effect of intra-building correlation on the resultant response can be shown by comparing these two. The acceleration response a_c at the corner of the top floor is used as the resultant response.

The directional acceleration responses of the top corner can be expressed as

$$a_{c,x}(t) = a_x(t) - a_\theta e_y(t) \quad a_{c,y}(t) = a_y(t) + a_\theta e_x(t) \quad (8)$$

where $a_{c,g}$ ($g = x, y, \theta$) is the resulting acceleration in the g direction at the corner; a_g is acceleration in the g direction at the origin; and e_x and e_y are the eccentricities of the corner from the origin in the x and y direction, respectively.

Standard deviations of the acceleration responses $a_{c,x}$ and $a_{c,y}$ can then be obtained from directly evaluating the resulting time history, i.e., variance of their associated time histories can be calculated directly. Clearly, correlation is considered inherently in this method.

Meanwhile, if correlation between a_x (or a_y) and a_θ is ignored, the resultant standard deviation at the corner can be calculated by

$$\sigma_{ac,x} = \sqrt{\sigma_{ax}^2 + e_y^2 \sigma_{a\theta}^2} \quad \sigma_{ac,y} = \sqrt{\sigma_{ay}^2 + e_x^2 \sigma_{a\theta}^2} \quad (9)$$

Eq. (9) is analogous to the SRSS method, where cross correlation is ignored. Comparing results calculated by Eq. (9) with those determined by direct time domain analysis will readily show the effects of correlation. Alternatively, one may include correlations in this combination rule by following the Complete Quadratic Commination (CQC) rule (e.g., Chen and Kareem, 2005).

We investigate the effects of correlation in three scenarios: the isolated building (labelled as *single*), two separate unlinked buildings ($S/B = 0.5$, labelled as *two buildings without link*) where correlation between wind-induced response components is fully aerodynamic, and case 2 of the previous LB cases, where correlation between wind-induced response components is both aerodynamic and structural.

Without loss of generality, we focus on along-wind acceleration (i.e., $a_{c,y}$) at the corner, which experiences the largest response, and the results are shown in Table 2 for each scenario. As can be seen, the correlation coefficient $\rho_{acc,yz}$ between wind-induced along-wind acceleration and torsional acceleration of the first scenario (*single*) is minimal because of weak correlation between the associated wind force components. Accordingly, values of $\sigma_{ac,y}$ in columns ② and ③ of Table 2 do not show significant differences for this scenario (③/② = 99%), indicating that ignoring correlation has almost no effect on the acceleration response of the isolated building.

Table 2 Comparison between standard deviation of along-wind acceleration response $a_{c,y}$

considering the correlation and that without considering the correlation (mm/s²)

scenarios	①	②	③	④
	$\rho_{acc,yz}$	$\sigma_{ac,y}$ considering correlation	$\sigma_{ac,y}$ ignoring correlation	③/②
single	-0.002	184	182	99%
two buildings without link	-0.06	205	194	95%
LBs	0.375	185	165	89%

In the second scenario (*two buildings without link*), the correlation coefficient $\rho_{acc, yz}$ between wind-induced along-wind acceleration and torsional acceleration remains small (-0.06, as listed in Table 2), although correlation between associated wind force components is significant (as shown in Fig. 24b). This means that for this scenario, correlation between wind force components does not necessarily lead to a high correlation between the associated wind-induced response components. The ratio ③/② is as high as 95% in this scenario, which suggests that error caused by neglecting correlation is within 5%.

In the third scenario (*LB*), on the other hand, the correlation coefficient $\rho_{acc, yz}$ between the two directional acceleration responses is as high as 0.375. In view of the fact that the correlation between associated wind force components is negative (shown in Fig 24b), it seems somewhat surprising that the correlation between the response components is positive. Clearly, this positive correlation between the response components is not the result of correlation between the associated wind force components. In fact, it is structural coupling induced by the link that gives rise to the positive correlation, because structural coupling in

the LBs couples the motion in the y direction positively with that in the θ direction (Song and Tse, 2014).

The above discussion clearly shows that although intra-building aerodynamic correlation for LBs is usually more significant than for an isolated building, the effect of this correlation on the wind-induced responses is insignificant. If link-induced structural coupling is ignored, the effect of intra-building aerodynamic correlation alone on the response of the LBs is smaller than 5%. Furthermore, the effect of intra-building aerodynamic correlation is much smaller than that of link-induced structural coupling. Correlation between the wind-induced responses, as a result, may even be completely different from that for the associated wind force components. Therefore, in addition to aerodynamic correlation, structural coupling caused by the link should also be considered when investigating the combined wind-induced responses.

5. Concluding Remarks

This study investigated inter- and intra-building aerodynamic correlations of linked buildings and their effects on their wind-induced response by employing spatiotemporal wind pressure data measured from a series of SMPMS wind tunnel tests.

It was shown that the inter-building correlation coefficient between two along-wind forces for $\alpha = 0^\circ$ decays as gap-to-breadth ratio increases, whereas for $\alpha = 90^\circ$, the coefficient increases with gap-to-breadth ratio. The inter-building correlation coefficient between two along-wind forces for the two critical wind directions, however, does not show a monotonic

variation with gap-to-breadth ratio. Furthermore, a positive relationship between the correlation coefficient ρ_{F*in} and the wind-induced response of the LBs was found for $\alpha = 0^\circ$. More specifically, if the inter-building correlation coefficient ρ_{F*in} is high, response in the associated LBs is large; if ρ_{F*in} is low, response in the associated LBs is small. For $\alpha = 90^\circ$, along-wind $r_{response}$ is positively related to ρ_{F*in} , which emphasizes the positive relationship. However, the positive relationship between ρ_{F*in} and cross-wind $r_{response}$ is undermined for $\alpha = 90^\circ$, because of the mixed effect of the varying force difference.

Intra-building correlation for LBs was compared with that for an isolated building. Correlation between along-wind and torsional wind force components on the isolated building is negligible, whereas for the LBs it is noteworthy, due to channeling effect. For smaller ratios of S/B the correlation is more pronounced. In addition, it was observed that the effect of intra-building correlation on the combination of associated wind-induced response components is not significant. In contrast, the influence from structural coupling caused by the link is even more significant. The effect of intra-building aerodynamic correlation is likely to be dwarfed by structural coupling, so correlation between response components can differ significantly from the associated wind force components. In view of this, a follow up study focusing on the combined effects of aerodynamic correlation and structural coupling may offer additional insight.

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