AERODYNAMIC CORRELATION OF LINKED BUILDINGS

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ABSTRACT

This paper investigates the intra-building and inter-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 few typical LBs with different gap distances are used to examine the two aerodynamic correlations. The intra-building aerodynamic correlation is examined using correlation coefficients and trajectories between wind force components on the building. Results show that the intra-building aerodynamic correlations for the LBs differ considerably from that for the isolated building, especially in the correlation between along-wind and torsional force components. The inter-building aerodynamic correlation is then presented in terms of the correlation coefficients between local wind force components and between generalized force components of the two buildings. The along-wind inter-building correlation is found to decrease with increasing gap distance, whereas the variation of cross-wind inter-building correlation is more complicated. In addition, it is illustrated that the wind-induced response of the LB is related positively to the correlation coefficient between the generalized force components of the two buildings in the associated unlinked case.

KEYWORDS

Inter-building force correlation; intra-building force correlation; wind force; wind-induced response; linked buildings; tall buildings.

INTRODUCTION

There is a growing trend to join tall buildings in close proximity by linking through horizontal structural links such as skybridges, skypools and skygardens. They are usually built to great heights in order to achieve a grand appearance, so wind-resistance is one of primary concerns in design practice, particularly in typhoon-prone areas. Because LBs are usually not far away from each other, wind flow around in their surroundings is susceptible to the interference effect (Kareem, 1987; Khanduri et al., 1998; Kim et al., 2011). In addition to modification of wind force magnitude on an LB, therefore, the correlation between wind force components within each building likely differs from that for an isolated building. This correlation, which is related to the combination of the resulting directional structural response (Thoroddsen et al., 1988; Tamura et al., 2001; Tamura et al., 2008; Tamura et al., 2014), is termed the intra-building aerodynamic correlation in this work. Furthermore, the existence of the structural link can couple the vibrations of the two connected buildings by transferring internal forces. Due to this link-induced structural coupling, 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; Song and Tse, 2014). This involves summing wind force components of all the connected buildings. For instance, the generalized force for a mode is the summation of generalized force components of all the connected buildings. The correlation in wind force components between the connected buildings, termed the inter-building aerodynamic correlation, plays an important role in determining the summation.

The effects from 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 and Inaoka, 1988; Khanduri et al., 1998; Lam et al., 2008; Kim et al., 2011; Hui et al., 2013). For instance, the interference effect was quantitatively examined for a principal building that was surrounded by one or more interfering buildings located at different locations, in terms of an interference factor (Bailey and Kwok, 1985; Sakamoto and Haniu, 1988; Taniike, 1992; Yahyai et al., 1992; Thepmongkorn et al., 2002; Mara et al., 2014). It should be mentioned that in these studies, usually only the principal building was equipped with instrumentation to measure wind forces and the interfering buildings were just dummy blocks to provide interference effect. As far as the authors of this paper know, very few studies examine the aerodynamic correlation of buildings in close proximity (Lim et al., 2011; Lim and Bienkiewicza, 2014), although the aerodynamic correlation for wind force components on a single building has been systematically investigated by Kareem (1982) and Tamura et al. (2000; 2001; 2008; 2014).

Therefore, there clearly remains a need to investigate both the intra-building and inter-building aerodynamic correlations of LBs, which provides the motivation for this study. In this study five LB models with designed determined gaps were fabricated to provide different intra-building and inter-building aerodynamic correlations. Fluctuating wind pressures on each face of the buildings in each model were simultaneously measured in a wind tunnel. Then, the intra-building and inter-building aerodynamic correlations were separately examined in detail. The main findings were summarized in the concluding section.

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 which were connected by a top link were set to be identical, as shown in Fig. 1. A typical square building model, 160 m tall and 30 m × 30 m in plan (prototype scale), was chosen for each building. Considering common arrangements of LBs, gap distance *S* was set to be in the range of 10 m to 45 m in the prototype scale. The specially-designed gap distance and ratio *S*/*B* for each case are listed in Table 1. For comparisons, the single isolated building case was also tested (labeled case 0). Allowing for the requirements of the block ratio and easy operation, a typical length scale of 1: 400 was selected for the models in the wind tunnel. One tested model in the wind tunnel (i.e., case 4, *S*/*B* = 1) is shown in Fig. 2.

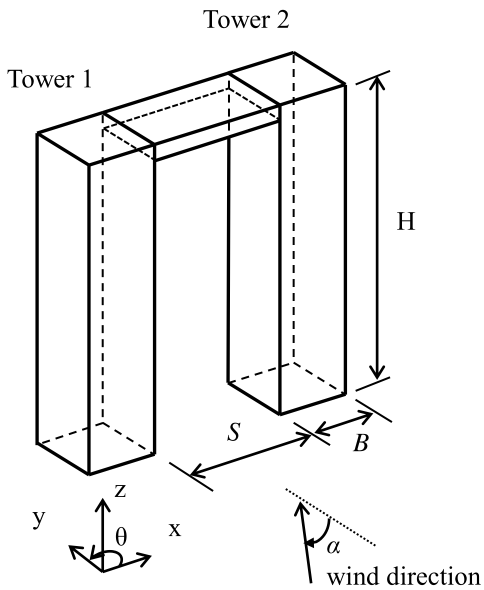


Figure 1 Setup of two square buildings, wind direction, and coordinate

Table 1 Gap distance (*S*) and ratio (*S*/*B*) for each case

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

The design mean wind speed and the longitudinal turbulence intensity at the top of the building (160 m) were 42.8 m/s and 13.9%, respectively. The approaching flow was simulated in the wind tunnel as natural wind over an open terrain with a power law exponent of 0.2 for the horizontal mean wind velocity profile. Both mean wind speed and turbulence intensity profiles were calibrated and the calibration results are shown in Fig. 3.

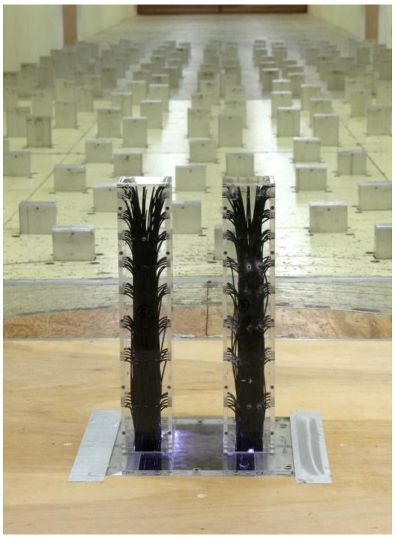


Figure 2 Model (case 4, S/B = 1) in the wind tunnel

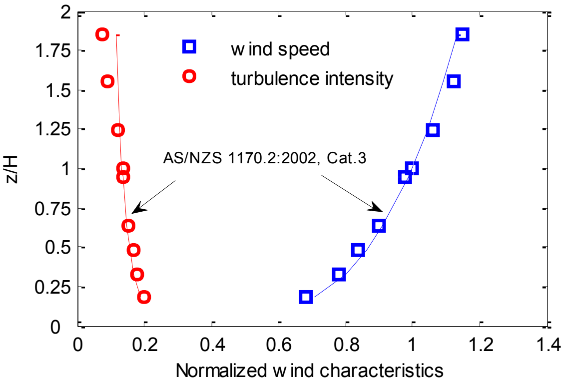


Figure 3 Simulated mean wind speed and turbulence intensity profiles

Pressures on the side faces of the model were measured employing a synchronous multi-pressure measuring system (SMPMS) with 9 levels of pressure taps on each face and 5 taps per level (360 taps in total). After fluctuating wind pressure data on all faces were synchronously collected, the time histories of local wind forces at each floor, two base overturning moments, and the base torque were determined by integrating over the associated wind pressure field.

INTRA-BUILDING AERODYNAMIC CORRELATION

The intra-building aerodynamic correlation, i.e., the correlation between wind force components on each building, is related to the combination of resultant directional wind-induced responses (Chen and Huang, 2009; Tamura et al., 2014). As mentioned in the introduction, the correlation may differ significantly from that for a single building. Therefore, the intra-building aerodynamic correlation is examined in this section. In this study, we focus on results for a critical wind direction, $\alpha = 0^o$. For $\alpha = 0^o$, the oncoming wind is normal to the face of the LBs and the two buildings are in a side-by-side symmetric arrangement (refer to Fig. 1). Therefore, the statistical characteristics of the aerodynamic forces on the two buildings are the same, and hence only results from the building on the right (Tower 2) will be discussed.

Trajectories of Base Moment Components

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

$$C_{MD} = \frac{M_D}{\frac{1}{2}\rho_{air} V_H^2 BH^2} \qquad C_{ML} = \frac{M_L}{\frac{1}{2}\rho_{air} V_H^2 BH^2} \qquad C_{MT} = \frac{M_T}{\frac{1}{2}\rho_{air} V_H^2 B^2 H} \tag{1}$$

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. ρ_{air} is the air density; and V_H is the velocity at the top of the building. In addition to examining the trajectories for the five LB cases, the trajectories for the associated single building are also presented for comparison.

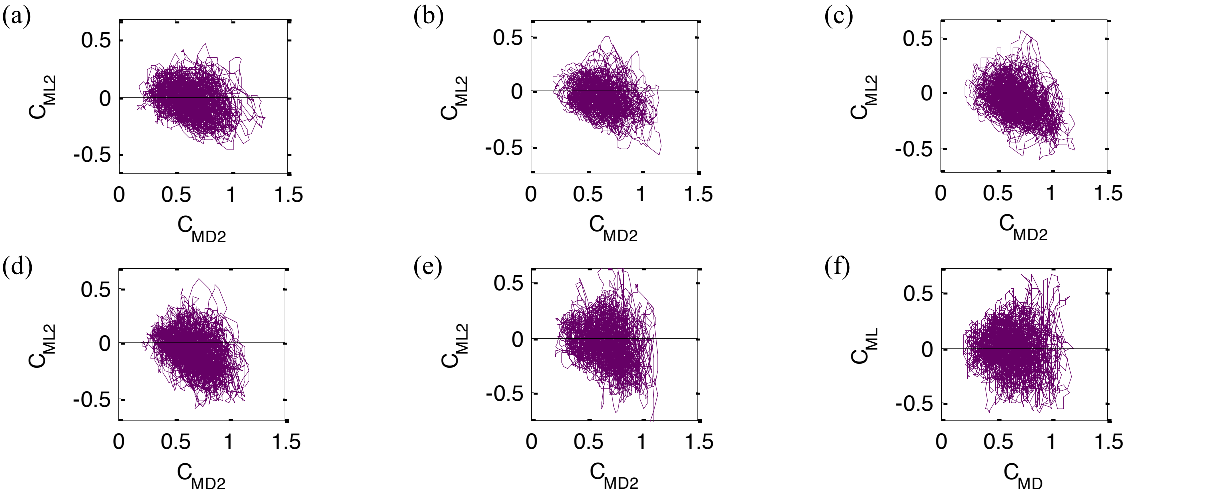
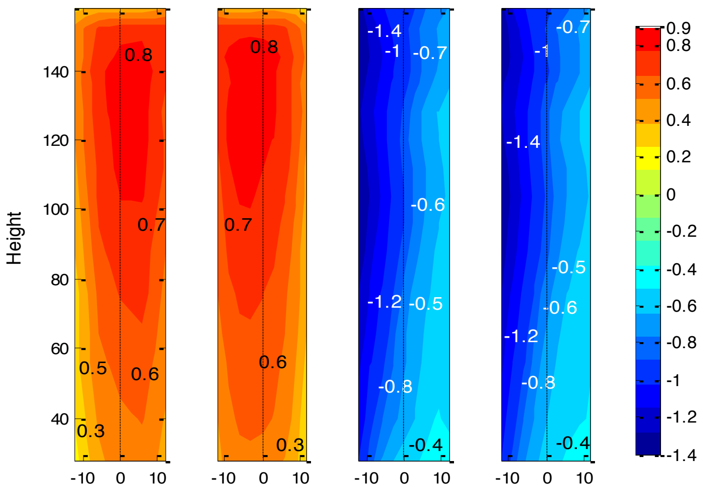


Figure 4 Trajectories for the along-wind and cross-wind base overturning moments: (a) S/B = 1/3; (b) S/B = 1/2; (c) S/B = 2/3; (d) S/B = 1; (e) S/B = 3/2; (f) single



(a) (b) (c) (d)

Figure 5 Contours of mean pressure 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 for the along-wind and cross-wind forces of all cases are shown in Fig. 4. For the single building, envelope of the trajectory (shown in Fig. 4f) is half-elliptic. This half-elliptic envelope is very similar to that reported in (Tamura et al., 2014), which in part suggests validation of the measured data. Unlike the symmetric trajectory for the single building, however, those for the LB cases shown in Fig. 4a to e are negatively inclined, clearly indicating a negative correlation between the along-wind and cross-wind forces. The negative correlation can be explained by the pressure contours shown in Fig. 5. Due to the channeling effect caused by the inter-building gap, the wind that flows through the gap accelerates. As a result, the pressure on the area of the windward faces close to the gap of is increased. Meanwhile, suction on the area of the two inside faces near the windward edges is also enhanced, as shown in Fig. 5. For Tower 2, pressure on its windward face is along the positive direction while suction on the inside face is along the negative direction, which causes the negative correlation between the along-wind and cross-wind forces. As channeling effect becomes relatively small when the gap distance is large, it can be seen that the trajectory for *S*/*B* = 2/3 is no more significantly inclined and becomes close to that for the single building.

The trajectories of the along-wind and torsional base moment are presented in Fig. 6. The trajectory for the single building shows a normal elliptic envelope, almost the same as that reported in (Tamura et al., 2014) for a square building with a similar aspect ratio. In contrast, the trajectories for the LBS cases (Fig. 6a 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. 5 where the distribution shifts inward), instead of being symmetric. In addition to causing the along-wind forces, the pressure with asymmetrical distribution will bring about torsional forces on the LBS. Therefore, the trajectories (shown in Fig. 6a to e) for the LB cases cluster within in a rather narrow zone, although the zone becomes relatively wider when *S*/*B* is large, such as when *S*/*B* = 3/2. Furthermore, the shape of the trajectories for LB shows that it is highly probable that maximal along-wind force coincides with maximal torsional force. Therefore, although the correlation between along-wind and torsional forces on a single building is weak and usually ignored, the correlation between the two wind force components on an LB is considerable and cannot be disregarded without careful consideration.

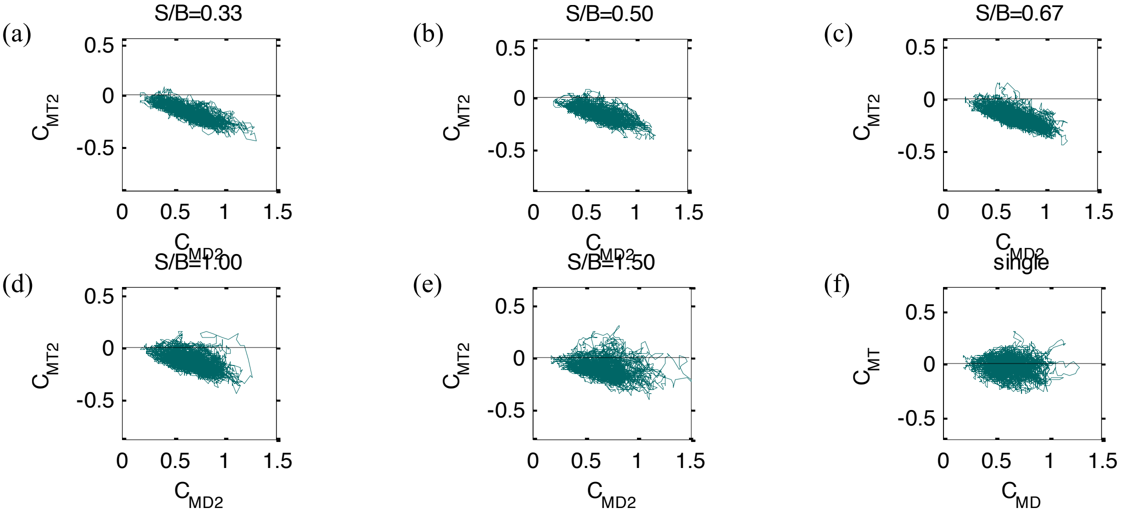


Figure 6 Trajectories for the along-wind and torsional base moments for $\alpha = 0^{o}$: (a) S/B = 1/3; (b) S/B = 1/2; (c) S/B = 2/3; (d) S/B = 1; (e) S/B = 3/2; (f) single

Trajectories for cross-wind base moment and torsional moment are presented in Fig. 7. It is usually believed that the cross-wind force and the torsional moment on a single building are well correlated, since they are both largely caused by the wake dynamics. As a result, the trajectory for a single building shown in Fig. 7f is an inclined ellipse, rather than a normal one. For the same reason, the trajectories for LBs also show similar envelopes to that for single building, indicating that the correlation between cross-wind and torsional force is similar for an LB and a single building. In addition, it can be observed that the gap distance ratio S/B has no significant effect on the trajectories.

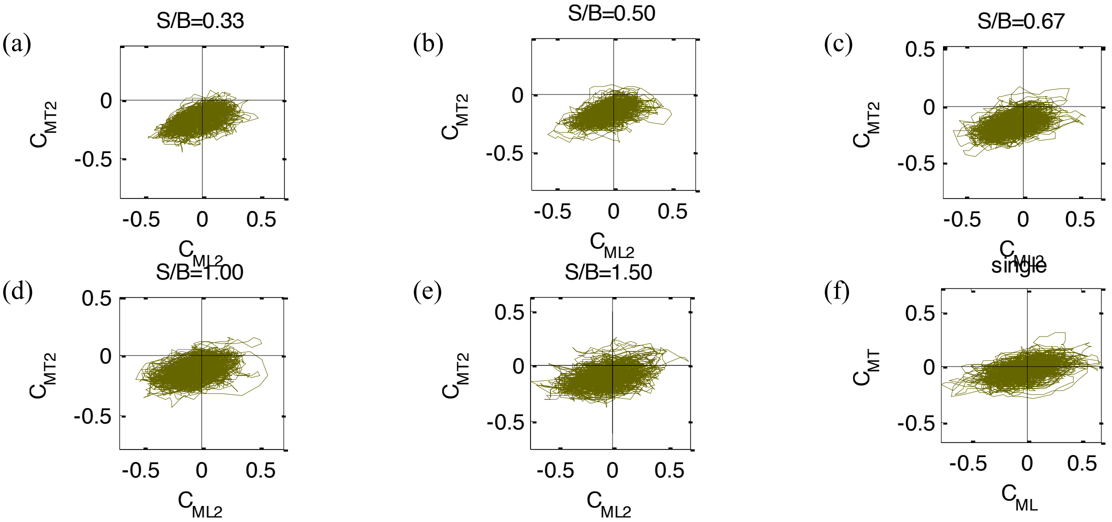


Figure 7 Trajectories for the cross-wind and torsional base moments for $\alpha = 0^{o}$: (a) S/B = 1/3; (b) S/B = 1/2; (c) S/B = 2/3; (d) S/B = 1; (e) S/B = 3/2; (f) single

INTER-BUILDING AERODYNAMIC CORRELATION

As indicated in the introduction, the inter-building correlation plays an important role in summing the wind force component of each building. This is because if the wind forces on two connected buildings are positively correlated, the summed generalized force for the whole LB system is relatively large and hence the response. However, if the wind forces are negatively correlated, the resultant general force is likely to be relatively small. In this section, the inter-building correlation is investigated quantitatively, to show how the correlation varies with gap distance.

Inter-building Correlation between Local Wind Force Components

The inter-building aerodynamic correlation is calculated in terms of the correlation coefficient between local wind force components, which is defined as

$$\rho_{Fc1,Fc2} = \frac{E\left\lfloor \left(F_{c,1}(z,t) - \mu_{Fc,1}\right)\left(F_{c,2}(z,t) - \mu_{Fc,2}\right) \right\rfloor}{\sigma_{Fc1}\sigma_{Fc2}} \tag{2}$$

where $F_{c,q}(z, t)$ is time histories of the force component on tower q (q = 1, or 2) at the elevation z, in which $c = D$ or L, denoting the along-wind and cross-wind force, respectively; $\mu_{Fc,\,q}$ and $\sigma_{Fc,\,q}$ are the mean value and standard deviation of the force component $F_{c,q}$; E is the expectation operator; and $\rho_{Fc1,Fc2}$ is the associated correlation coefficient.

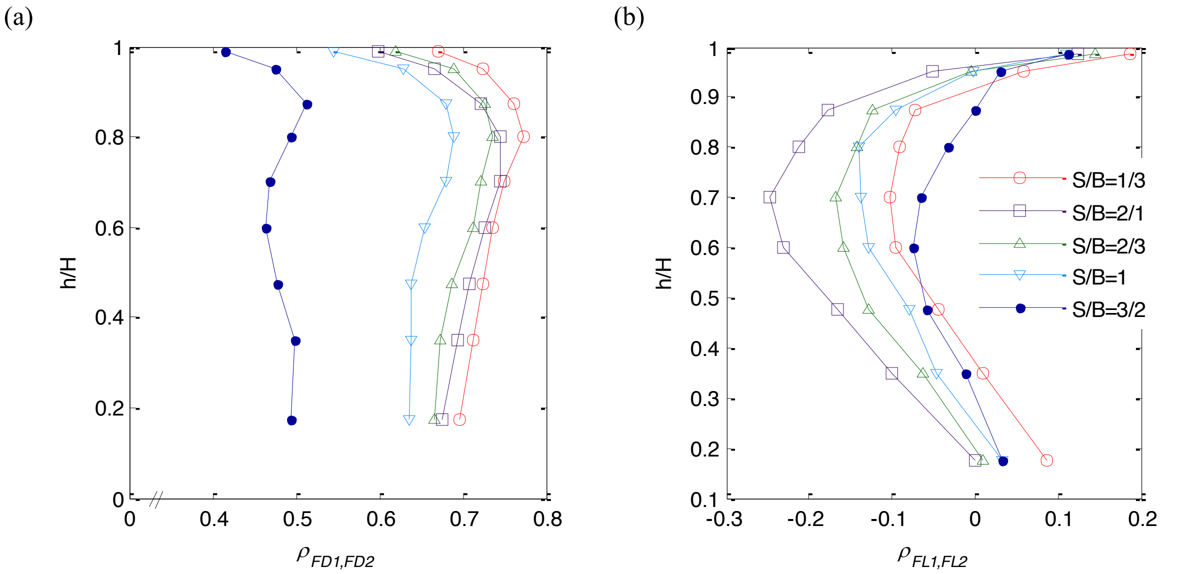


Figure 8 Correlation coefficients between two wind force components on Towers 1 and 2 at the same level for α = 0º: (a) along-wind; (b) cross-wind

Fig. 8 shows the correlation coefficients between the local wind forces on the two buildings of the five cases for α = 0º. It can be observed from Fig. 8a that in 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, it can be anticipated that for α = 0º, when S/B is very large (> 3/2), the correlation between along-wind forces on two buildings will become relatively weak. However, it should be noted that the wind forces at high levels (h/H > 0.8) for S/B = 1/2 and 2/3 do not stringently follow this trend. This strange variation could be attributed to the complicated 3D flow (tip flow) around the building top. When S/B increases from 1/2 to 2/3, the 3D flow may increase the correlation between suction forces on the two leeward faces, to some extent delaying the decrease of the correlation between the forces on the two windward faces and hence resulting in the correlation coefficients not decreasing significantly from S/B = 1/2 to 2/3.

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 though a week trend exists. In the range 0.3 < h/H < 0.9, the absolute values of the correlation coefficients increase with increasing S/B from 1/3 to 1/2, whereas further increasing S/B from 1/2 to 3/2 leads to gradual decrease in the absolute value of the correlation coefficients. The increase in the correlation coefficient can be explained by the increased gap flow—

accelerated wind passing through the gap may increase the correlation between the two suction forces on the two inner faces. The decrease in the correlation coefficient, on the other hand, is due to the fact that increases in *S*/*B* above 1/2 can gradually allow the shear layers from the two inner edges to roll up into the rear region of the two towers through the gap, interrupting the original cross-wind correlation in *S*/*B* = 1/2. In addition, within the range 0.3< *h*/*H* < 0.9, almost all the 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 which 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, even becoming positive. 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).

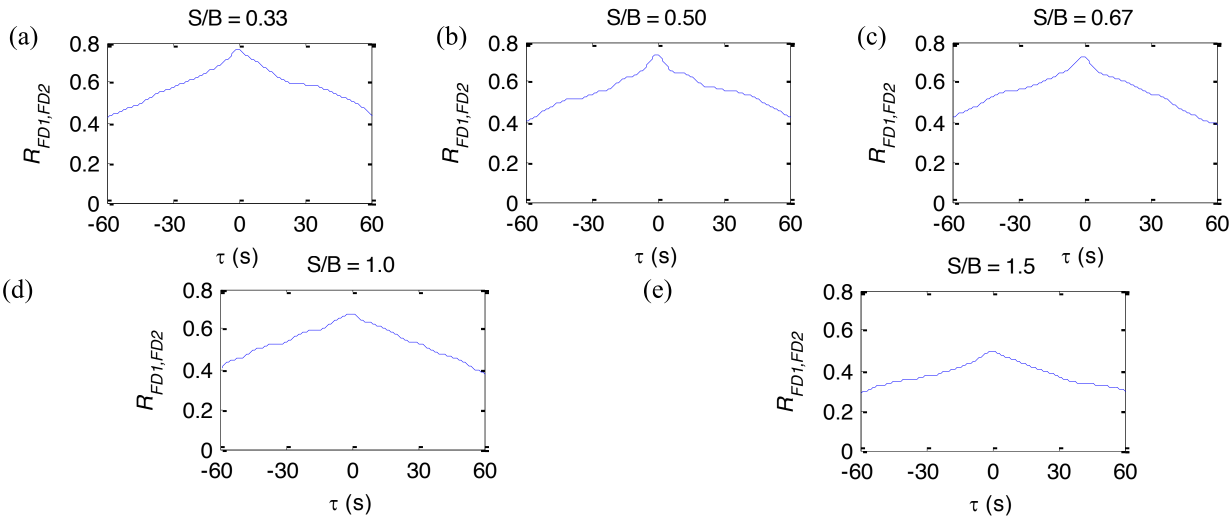


Figure 9 Inter-building correlation function between along-wind forces at 0.8*H* for *α* = 0°: (a) S/B = 1/3; (b) S/B = 1/2; (c) S/B = 2/3; (d) S/B = 1; (e) S/B = 3/2

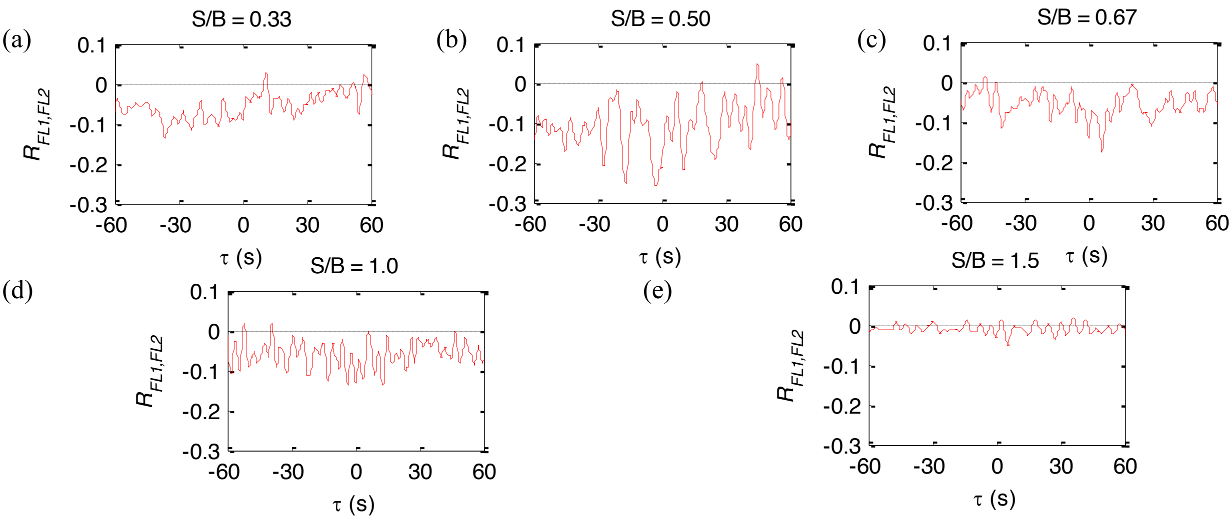


Figure 10 Inter-building correlation function between cross-wind forces at 0.8*H* for *α* = 0°: (a) S/B = 1/3; (b) S/B = 1/2; (c) S/B = 2/3; (d) S/B = 1; (e) S/B = 3/2

In addition to the spatial correlation coefficient, the inter-building temporal correlation function *R* for time lag *τ* is also calculated for the local wind forces at a representative height of 0.8H, as shown in Figs. 9 and 10. For the along-wind forces, it can be observed from Fig. 9 that for all cases, the zero time lag has the largest value and the correlation decays significantly with increasing time lag *τ*. Furthermore, for most of the time lags, the value of the associated correlation function decreases with increasing gap distance 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 shown in Fig. 10. As can be seen, the largest correlation does not occur at the zero time lag and the correlation does not monotonically decay with increasing time lag. For instance, the largest correlation shows at *τ* = -2.4s and 6.6s, for *S*/*B* = 1/2 and 2/3, respectively. More interestingly, it can be observed that the correlation function R has embedded periodicity, albeit rather weak. Although there is no perfect coherent periodic vertex shedding in the LSs, the pressures on two outer side faces of the LBs still introduced some periodicity in the inter-building correlation between cross-wind forces.

Effect of Correlation on the Wind-induced Responses of LBs

In this section, the effects of inter-building correlation on the wind-induced responses of LBs are examined. Five LBS cases with different gap distances are considered. In order to highlight the effects from inter-building wind load correlation, modal properties of the five LBS cases are assumed to be identical to those in case 2 (S/B = 1/2). In this way, the structural coupling due to the link is equal in these five cases and thus the difference between the resulting responses can be attributed only to aerodynamic forces. The structural system for case 2, which is the same as that in Song and Tse (2014). The first three frequencies of the system are 0.239 Hz (x direction), 0.239 Hz (y direction), and 0.297 Hz (θ direction). A damping ratio of 2% is set for all modes.

Due to the link-induced structural coupling, the two connected towers in an LBS behave as a whole to resist the external wind forces. Therefore, the wind forces on both towers should be considered simultaneously to precisely determine their wind-induced responses. For example, the j-th generalized force F^*_j on the overall LBS is the summation of generalized force components from both towers, so,

$$\begin{aligned} F_j^*(t) &= F^*_{j,tower1}(t) + F^*_{j,tower2}(t) \\ &= \sum_{i=1}^{m} F_{c,1}(z_i,t)\,\Phi_{tower1,j}(z_i) + \sum_{i=1}^{m} F_{c,2}(z_i,t)\,\Phi_{tower2,j}(z_i) \end{aligned} \tag{3}$$

where $\Phi_{tower1,j}$ and $\Phi_{tower2,j}$ are the j-th mode shape components of Tower 1 and Tower 2, respectively; and $F^*_{j,tower1}$ and $F^*_{j,tower2}$ are the generalized wind force components of Tower 1 and Tower 2, respectively. Clearly, the inter-building correlation between the generalized force components of the two towers (i.e., $F^*_{j,tower1}$ and $F^*_{j,tower2}$) implicitly presents in Eq. 3 and plays an important role in the summation and hence has an influence on the related wind-induced responses.

Fig. 11 shows the inter-building correlation coefficients ρ_{F^*in} between the generalized force components of the two towers without a link (i.e., the unlinked case) for the first in-phase modes in along-wind and cross-wind directions. It can be observed that the correlation coefficient ρ_{F^*in} for the along-wind forces decreases gradually as the gap distance increases, because the correlation between along-wind forces on the two towers (i.e., $F_{tower1}(z, t)$ and $F_{tower2}(z, t)$) decays with the increase of gap distance, as shown in Fig. 8a. However, ρ_{F^*in} for cross-wind forces does not vary in the same manner with the gap distance ratio S/B. This is because cross-wind forces result from the pressure fluctuations under the separated shear layer from the side faces and hence the associated correlation may not bear a direct relationship with gap distance. Other tertiary influences also play a role like the turbulence from building edges. Similar to the variation shown in Fig. 8b, the correlation for the cross-wind forces increases when S/B increases from 1/3 to 1/2, whereas decreases when S/B increases from 1/2 to 3/2.

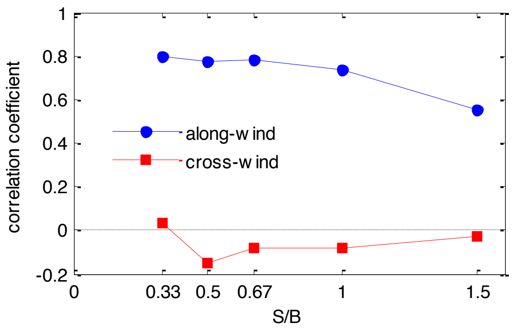


Figure 11 Correlation coefficient ρ_{F^*in} for all LB cases

In order to quantify the effect of the inter-building aerodynamic correlation on the wind-induced responses, a ratio $r_{response}$ is introduced, which is defined as

$$r_{response} = \frac{\sigma_{acc,link}}{\sigma_{acc,nolink}} \tag{4}$$

where $\sigma_{acc,\,link}$ is the standard deviation of the top acceleration response in the case of an LBS; $\sigma_{acc,\,nolink}$ is that in the associated unlinked case.

The relationship between the inter-building correlation coefficient ρ_{F^*in} and $r_{response}$ is illustrated in Fig. 12. Clearly, for both along-wind and cross-wind responses, $r_{response}$ increases with increasing ρ_{F^*in}. This indicates that when ρ_{F^*in} is large in the unlinked case, installing a link (even with large stiffness) does not significantly decrease the response in the associated LBS. This is because large value of ρ_{F^*in} means that the resulting in-phase generalized force component is relatively large, whereas the resulting out-of-phase generalized force component is relatively small. It has been confirmed in (Song and Tse, 2014) that link's stiffness only increases the frequency of the out-of-phase mode and thus only decreases the out-of-phase response component. Therefore, if the out-of-phase generalized force component is small (i.e., ρ_{F^*in} is large), the minor decrease in the out-of-phase modal response component will not lead to significant reduction in the total response. However, when ρ_{F^*in} is small, the response in the associated LBS can be reduced significantly, because in this case the out-of-phase response component is relatively considerable. For instance, the value of ρ_{F^*in} for along-wind response in S/B = 1/3 is large (0.8) so the value of $r_{response}$ is up to 90%, indicating that for this case installing a link has no significant effect on the reduction of response in the along-wind response. In contrast, the value of ρ_{F^*in} for along-wind response in S/B = 3/2 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 to the response in the associated unlinked case. In addition, it can be observed that reduction in cross-wind response is more significant than that in along-wind response, because the correlation coefficient ρ_{F^*in} between cross-wind forces is much smaller than that between along-wind forces. All these results clearly emphasize that the inter-building correlation plays a significant role in determining the reduction in the response of LBs.

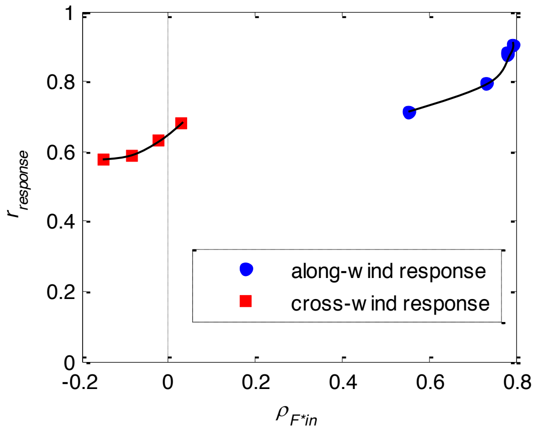


Figure 12 Relationship between the inter-building correlation coefficient ρ_{F^*in} and the response ratio $r_{response}$

CONCLUSIONS

This study investigated the intra-building and inter-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. The intra-building correlation for LBSs was compared with that for a single building. The correlation between along-wind and torsional wind force components on the single building is negligible, whereas the correlation for the LBSs is noteworthy, due to the channeling effect. For smaller ratios of S/B the correlation is more pronounced. It was shown that for the examined wind direction (i.e., $\alpha = 0^o$) and the building configurations considered, the inter-building correlation between two along-wind forces decays with the increase of gap distance, whereas that between the cross-wind forces does not show a similar relationship with the gap distance. In addition, it was illustrated that inter-building correlation has an important effect on the wind-induced response of LBSs. For the same link, if the inter-building correlation coefficient ρ_{F^*in} is high, there is no significant reduction in the response of the associated LBSs (compared to the two buildings without a link). However, if the correlation coefficient ρ_{F^*in} is low, the associated LBSs can show significant reduction in the response. In short, there is a positive relationship between the correlation coefficient ρ_{F^*in} and the wind-induced response of LBSs.

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