Wind and Structures, *Vol. 18, No. 4 (2014) 443-456*
DOI: http://dx.doi.org/10.12989/was.2014.18.4.443

Wind tunnel investigation of correlation and coherence of wind loading on generic tall twin buildings in close proximity

Juntack Lim[*1] and Bogusz Bienkiewicz[2a]

[1]*Construction Technology Center, Samsung Corporation, Korea*
[2]*Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523, USA*

(Received February 23, 2012, Revised August 15, 2012, Accepted August 16, 2012)

Abstract. A popular modern architectural form for tall buildings is two (or more) towers which are structurally linked through such features as a shared podium or sky-bridges. The fundamental features of the wind loading and the structural links of such buildings can be studied by measuring load components on the individual unlinked towers along with their correlations. This paper describes application of dual high frequency force balance (DHFFB) in a wind tunnel study of the base wind loading exerted on generic tall twin buildings in close proximity. Light models of two identical generic tall buildings of square plan were mounted on DHFFB and the base wind loading exerted on the buildings was simultaneously acquired. The effects of the relative positions of the buildings on the correlations and coherences involving loading components on each building and on the two buildings were investigated. For some relative positions, the effects of the building proximity on the wind loading were significant and the loading was markedly different from that exerted on single buildings. In addition, the correlations between the loadings on the two buildings were high. These effects have potential to significantly impact, for example, the modally-coupled resonant responses of the buildings to the aerodynamic excitations. The presented results were not meant to be recommended for direct application in wind resistant design of tall twin buildings. They were intended to show that wind loading on tall buildings in close proximity is significantly different from that on single buildings and that it can be conveniently mapped using DHFFB.

Keywords: correlation; coherence; base wind loading; wind tunnel testing, dual high-frequency force balance; tall twin buildings; building coupling

1. Introduction

The design of modern tall buildings involves the evaluation of the effects of surrounding tall structures on the aerodynamic response of the buildings under consideration. For over the past three decades, a host of generic studies addressing such interference effects have been reported in open literature. Saunders and Melbourne (1979), Huang and Gu (2005), Lam *et al.* (2008) have evaluated these influences by examining aerodynamic loading on or wind-induced response of a primary (instrumented) building in the presence of interfering (dummy) building or buildings. Thoroddsen *et al.* (1988) and Ni *et al.* (2001) have addressed the significance of correlation

∗Corresponding author, Graduate Research Assistant, E-mail: bogusz@engr.colostate.edu
[a] Professor

http://www.techno-press.org/?journal=was&subpage=8 ISSN: 1226-6116 (Print), 1598-6225 (Online)

between components of wind loading on a tall building as affected by a nearby interfering building.

The above efforts have significantly improved understanding of wind loading on and aerodynamic response of tall buildings surrounded by other buildings or structures of comparable height. Most of the reported studies have been based on wind tunnel data obtained using a single high-frequency force balance (HFFB). Application of such data for cases involving tall twin buildings in close proximity is limited since buildings in such configurations may be structurally linked. This limitation is overcome when a dual-HFFB (DHFFB) is used to measure the aerodynamic loading (Boggs and Hosoya 2001, Xie and Irwin 2001, and Lim and Bienkiewicz 2007).

In the presence of structural coupling, precise mapping of the inter-building wind loading correlations and coherences is needed for accurate prediction of the building aerodynamic response. Current understanding of these parameters and their effects on the building response is incomplete due to the complexity of the problem, and a limited number of related investigations and data published in the open literature.

This paper describes application of DHFFB in a wind tunnel study of the base wind loading exerted on generic tall twin buildings in close proximity. Light models of two identical tall buildings of square plan were mounted on DHFFB and the base wind loading exerted on the buildings was simultaneously acquired. The effects of the relative positions of the buildings on the correlations and coherences involving loading components on each building and on the two buildings were investigated. First, the experimental set-up, building models and instrumentation are described. Then, the representative results, the correlation and coherence of various wind loading components, are discussed. These properties were computed for the wind loading components exerted on the same building (they are denoted hereafter as building correlations and coherences) and for the loading components on the two buildings (denoted hereafter as inter-building correlations and coherences). The results obtained for each building of the twin building configuration are compared with those for an isolated tall building. The findings of this study are summarized in the concluding section of the paper.

2. Experimental set-up

2.1 Dual-HFFB system

A dual-HFFB (DHFFB) system developed at the Wind Engineering and Fluids Laboratory (WEFL) at Colorado State University (CSU) was used in measurements of base wind-induced loading on models of two buildings in close proximity. It consisted of two high-frequency force balances (ATI Inc., Model: Gamma US-15-50) and a mechanical support system. The balances were electronically synchronized to allow for simultaneous acquisition of the measurements from ten data channels – five components of the base wind loading – sampled from the two balances. The DHFFB was fastened to a rigid support system that was designed to accommodate precise and versatile modifications of the tested twin building configuration.

2.2 Flow simulation

The wind tunnel testing was carried out in a boundary-layer wind tunnel (the Meteorological Wind Tunnel) at WEFL. The ABL (atmospheric boundary layer) flow was modeled at a 1:500 geometrical scale based on the turbulence intensity and the length scale. The approach flow represented a wind exposure with a power law exponent of 0.21. The turbulence intensity at the building rooftop level was 12%. Further details on the technique employed in modeling of this flow and on the flow properties are presented by Lim *et al.* (2006).

2.3 Twin building configurations

The considered twin building (TB) configuration comprised of two identical buildings, 38 m x 38 m in plan and 305 m in height. Fig. 1 shows the coordinate system and the grid used to define the relative positions of the buildings. During the wind tunnel testing, the location of the interfering building B1 was varied, while the position of the primary building B2 was kept unchanged. As indicated in Fig. 1, X/D (Y/D) is the normalized (non-dimensional) spacing between the building centers, in the X (Y) direction. Accordingly, for the buildings in contact, with their centers located on the Y axis, X/D = 0.00 and Y/D = 1.00. Similarly, for the buildings in contact, with their centers on X axis, X/D = 1.00 and Y/D = 0.00. The wind tunnel testing described in this paper was carried out for the wind direction aligned with the *x*-axis, as indicated in Fig. 1.

2.4 Data acquisition

The wind-induced base moments and torques exerted on the two building models were simultaneously acquired at a sampling rate of 2000 data samples per second. Thirty six segments of the data, each comprising of 16384 data points, were acquired for the considered spacing of the buildings. The collected data were subsequently used to calculate the building and inter-building correlations and coherences of the components of the base wind loading.

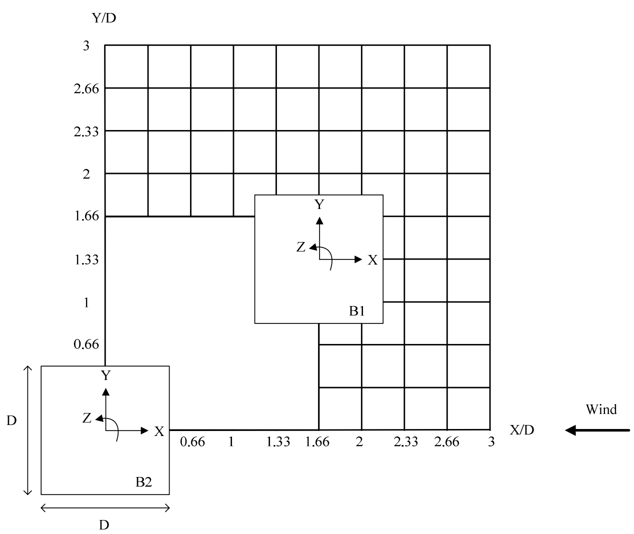


Fig. 1 Twin building configuration and reference coordinate systems

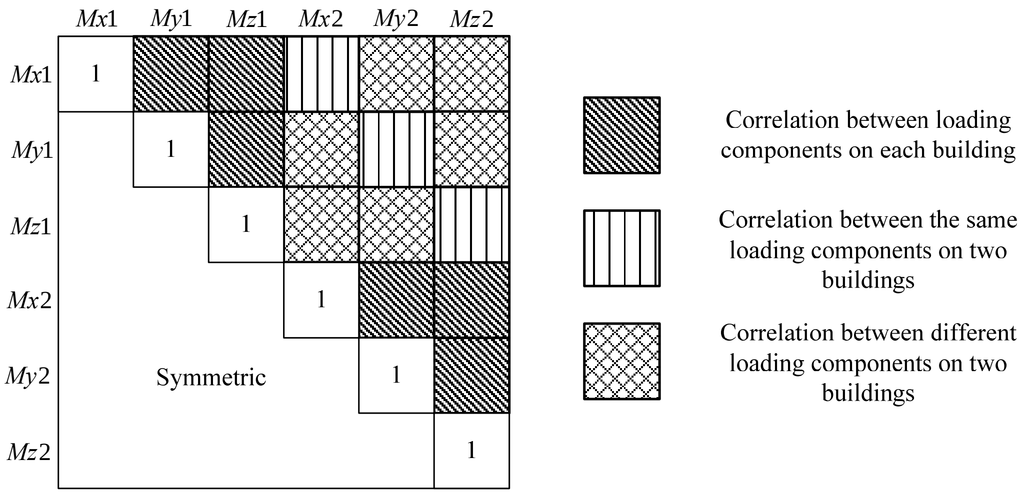


Fig. 2 Schematic representation of wind loading correlation matrix

3. Loading correlation matrix

The wind loading correlations and coherences discussed in this paper are schematically indicated using a 6 x 6 symmetric matrix shown in Fig. 2. In presence of the structural coupling between the buildings, the off-diagonal elements of the loading correlation matrix could be pivotal in predictions of the building response and they should be retained in structural analysis. Herein they are divided into the following three groups: (a) the correlations between loading components on each building, (b) the correlations between the same loading components on the two buildings and (c) the correlations between different loading components on the two buildings. These groups are schematically depicted in Fig. 2. The first group (a) is denoted as the “building coupling” of wind loading components, while the second (b) and the third (c) are labeled as the “inter-building coupling”. Overall, these correlations are the result of the flow-structure interaction commonly termed as the aerodynamic coupling (Lim and Bienkiewicz 2007).

4. Results and discussion

4.1 Building correlations

Fig. 3 presents the correlation coefficients (ρ) of the cross-wind (M_x), along-wind (M_y) and torsional (M_z) loading (base moment) components on buildings B1 and B2. The relative orientation of the buildings and the wind loading components involved in the correlations (marked in boldface) are schematically indicated in inserts in Fig. 3, see also Fig. 1. Vector notation is used to denote the sway moments M_x and M_y. The cross-wind moment (M_x) denotes the overturning moment about x-axis, while the along-wind moment (M_y) indicates the overturning moment about y-axis. The borders of zones (of locations of building B1) exhibiting high correlations are marked using dash lines.

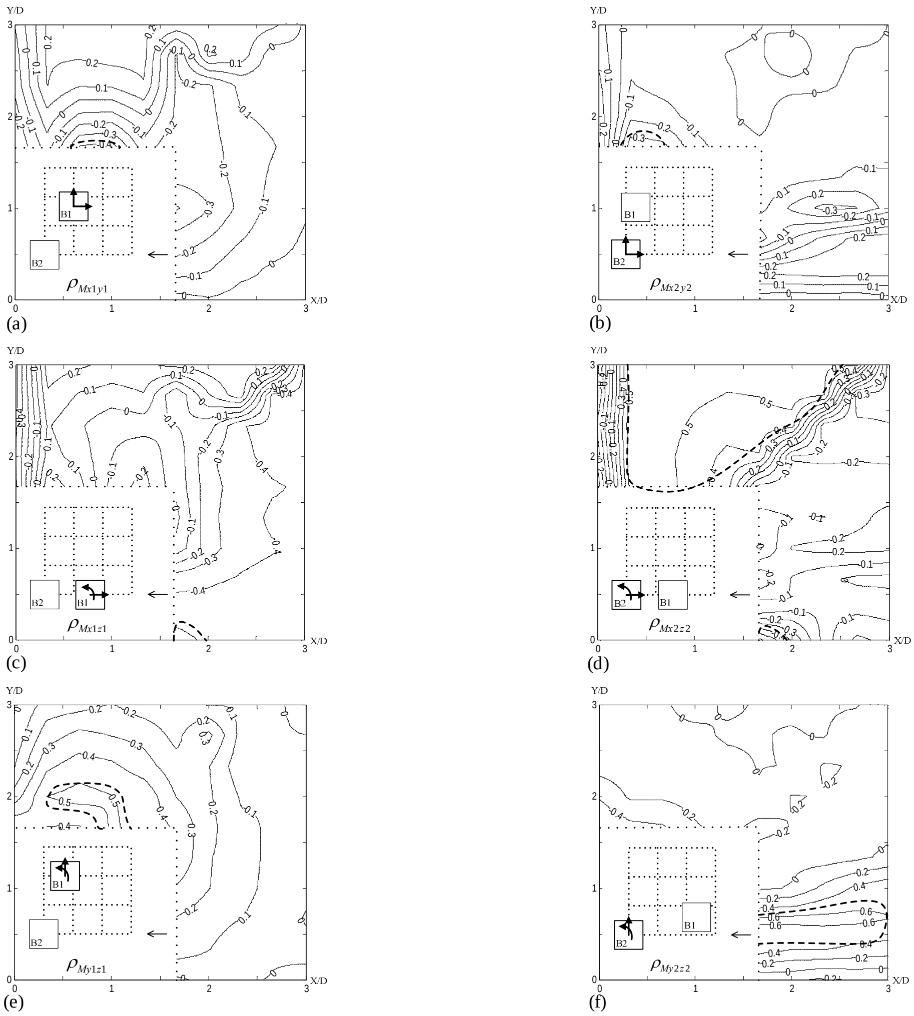


Fig. 3 Building correlations of wind loading components

As can be observed in Figs. 3(a) and 3(b), the magnitude of the cross-wind/along-wind building correlation coefficients (ρ_{Mx1y1} and ρ_{Mx2y2}) was large, up to 0.45, at some locations of the interfering building B1, e.g. (X/D, Y/D) = (1, 1.66) for loading on building B1 (ρ_{Mx1y1}) and (X/D, Y/D) = (0.33, 1.66) for loading on building B2 (ρ_{Mx2y2}). However for most of the configurations these coefficients were lower than 0.2. The cross-wind/torsional correlations (ρ_{Mx1z1} and ρ_{Mx2z2}), Figs. 3(c) and 3(d), were at most locations lower than the cross-wind/torsional correlation for the single building (SB) case, discussed below. For building B1, the highest magnitude of the correlation (0.54) was observed for Y/D = 0, see Fig. 3(c), while for building B2 the highest value of ρ_{Mx2z2} was 0.62 and it occurred when building B1 was located at (X/D, Y/D) = (1.66, 0), Fig. 3(d). At some locations the correlation magnitude was small. It was found that the along-wind and torsional loadings (M_y and M_z) on both the buildings were highly correlated (ρ_{My1z1} and ρ_{My2z2}). The highest magnitude of ρ_{My1z1} (0.54) was observed for building B1 located at (X/D, Y/D) = (0.66, 2), Fig. 3(e). The largest observed value of ρ_{My2z2} was 0.66 and it occurred when building B1 was upstream of B2 and Y/D = 0.66, see Fig. 3(f). These results indicate that, depending on the relative positions of the buildings, all the wind loading components on each building can be strongly correlated (aerodynamically coupled).

The above findings are in contrast with an isolated (single) building (SB) case, where for buildings of generic rectangular (prismatic) geometry only the cross-wind/torsional correlation (ρ_{Mxz}) is significant. For such a case, representative values of the correlation coefficients, used herein as the reference values, were determined by the authors, Lim *et al.* (2006), during a related wind tunnel study carried out at WEFL. Their magnitudes were 0.02, 0.53 and 0.13, respectively, for the along-wind/cross-wind (ρ_{Myx}), cross-wind/torsional (ρ_{Mxz}) and along-wind/torsional (ρ_{Myz}) components. Similar values were reported by Tallin and Ellingwood (1985) and Makino and Mataki (1993).

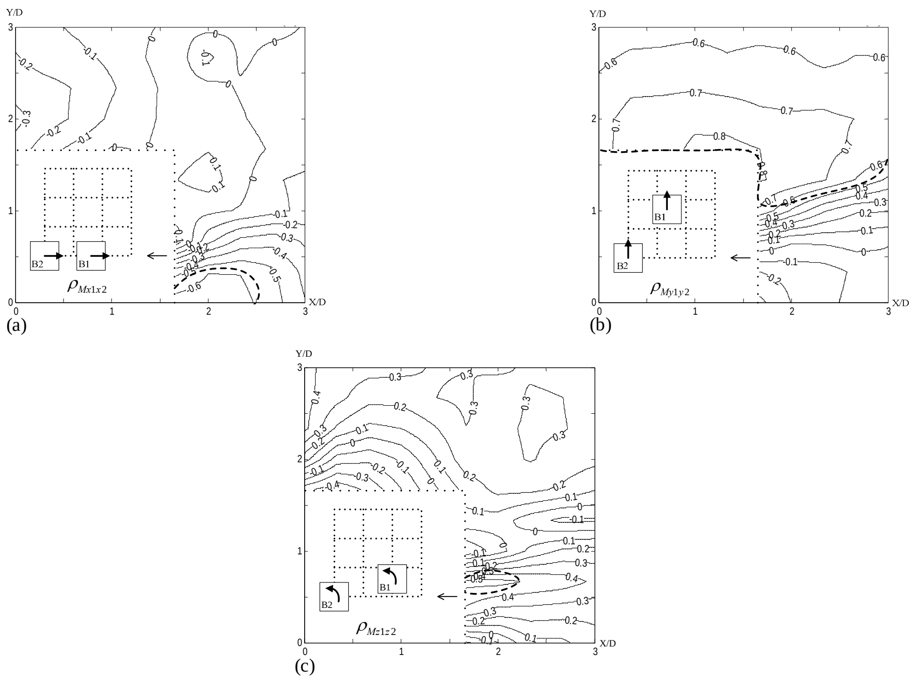


Fig. 4 Inter-building correlations of the same loading components

4.2 Inter-building correlations

As defined in Sec. 3, the correlations of wind loading components on the two buildings are labeled as inter-building correlations. For the same components, these correlations are presented in Fig. 4. As can be seen, for the crosswind components (M_{x1} and M_{x2}), very high correlation ρ_{Mx1x2} (the magnitude of 0.68) was obtained when the two buildings were aligned with wind (X/D > 1.66, Y/D < 0.33), a dashed region in Fig. 4(a). In the remaining region, the correlation was significantly lower. An opposite trend was observed for the along-wind correlation (ρ_{My1y2}), Fig. 4(b). The high correlation occurred for Y/D > 1.33, with the largest value of approximately 0.83. In the case of the torsional components (M_{z1} and M_{z2}), Fig. 4(c), the largest correlation ρ_{Mz1z2} = 0.54 was found when the building B1 was located upstream of B2 (X/D = 2, Y/D = 0.66). These results suggest that the same loading components induced on the two buildings in close proximity are strongly coupled.

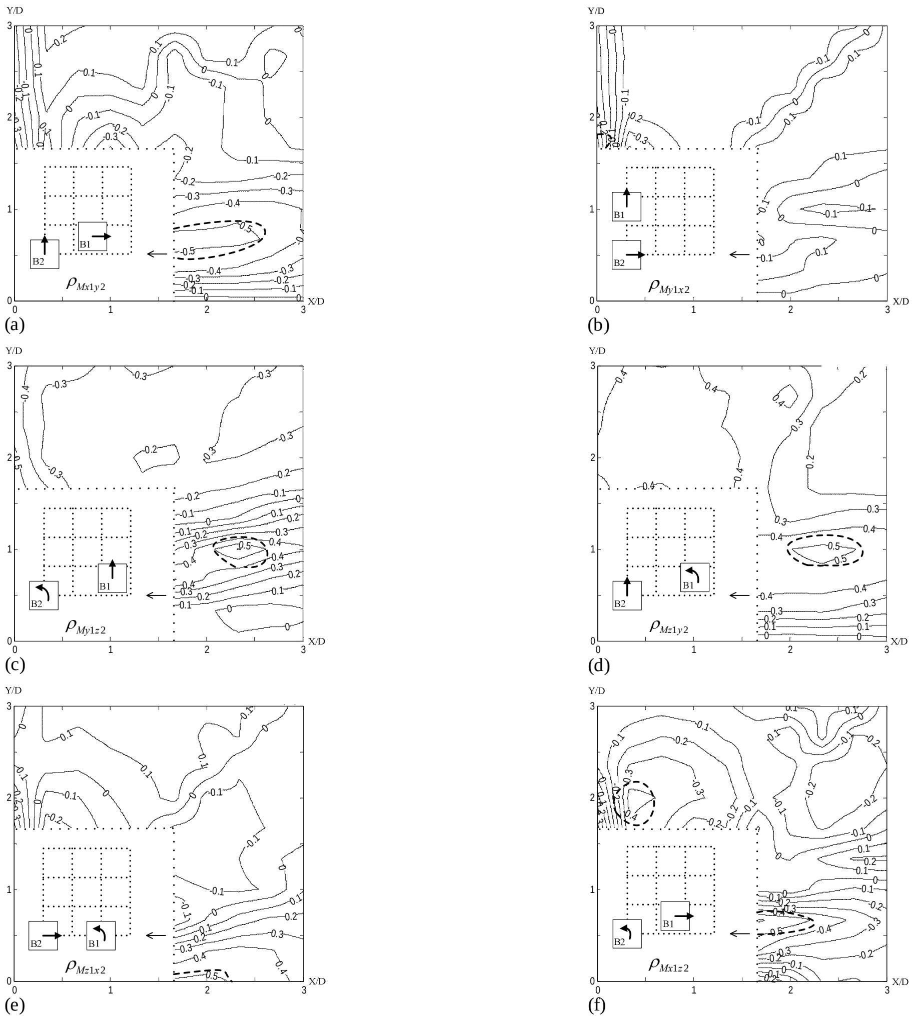


Fig. 5 Inter-building correlations of different loading components

Fig. 5 shows the inter-building correlations of different loading components. As can be seen in Fig. 5(a), the crosswind component on building B1 was highly correlated with the along-wind component on building B2, and the magnitude of ρ_{Mx1y2} reached up to 0.55. On the other hand, the along-wind/cross-wind correlation (ρ_{My1x2}), Fig. 5(b), was very low, except for (X/D, Y/D) = (0, 1.66).

In the case of the along-wind/torsional correlations ρ_{My1z2}, Fig. 5(c), and ρ_{Mz1y2}, Fig. 5(d), the highest magnitude of the coefficient was 0.63 and it occurred when building B1 was placed upstream of B2 (X/D, Y/D) = (2.33, 1). For Y/D < 0.33 the correlations were negligible (< 0.2). The largest magnitude of the crosswind-torsional correlations (ρ_{Mz1x2} and ρ_{Mx1z2}, Figs. 5(e) and 5(f)) was 0.61 and it occurred when the building B1 was located upstream of B2 (X/D < 2.33, Y/D < 0.33) for ρ_{Mz1x2}, Fig. 5(e), and (X/D < 2.33, 0.5 < Y/D < 1) for ρ_{Mx1z2}, Fig. 5(f). In addition, high correlation, ρ_{Mx1z2}, was observed at (X/D, Y/D) = (0.33, 2), Fig. 5(f).

The above results indicate high inter-building coupling between the same as well as different components of wind loading on tall buildings in close proximity. Use of DHFFB allows for accurate quantification of this coupling.

4.3 Critical building spacing

Fig. 6 schematically shows the locations of building B1 associated with the highest magnitude of the building and inter-building correlations. It can be seen that significant correlations, the magnitude of the correlation coefficient ranging from 0.37 through 0.83, are exhibited when building B1 is placed in the following (X/D, Y/D) regions: (1.66-2, 0), (1.66-2.33, 0.66), (0-1.33, 1.66), and (0.66, 2). These locations are within the range of interest in design of twin tall buildings. Further analysis of wind loading was carried out for these cases. The coherences of the loading components are discussed next.

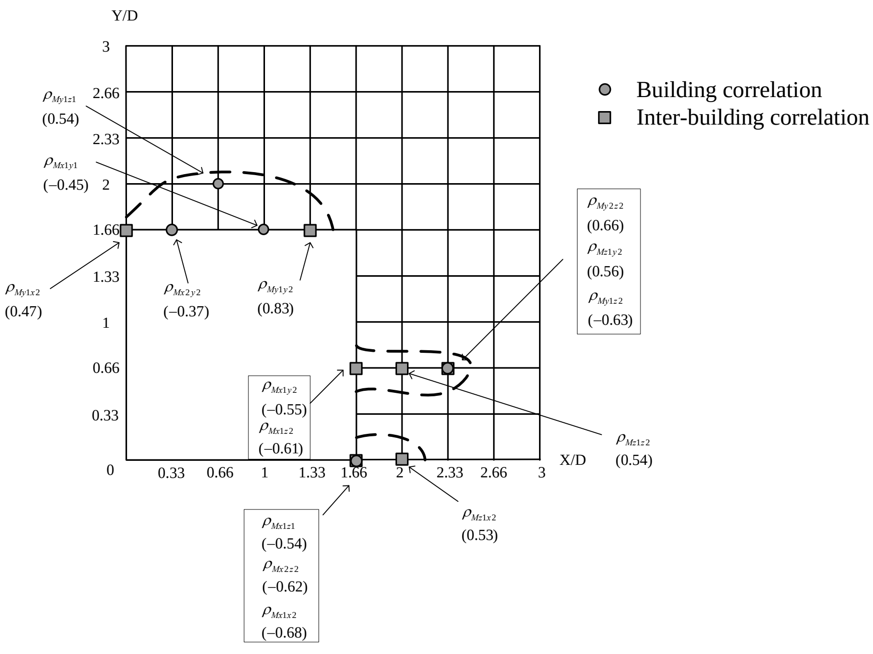


Fig. 6 Building locations associated with the highest wind loading correlations

4.4 Wind loading coherences

The coherence is defined as

$$Coh_{Mxy}(f) = \frac{\left|S_{Mxy}(f)\right|}{\sqrt{S_{Mxx}(f)S_{Myy}(f)}} \tag{1}$$

where $S_{Mxx}(f)$ and $S_{Myy}(f)$ are, respectively, the power auto-spectra of M_x and M_y components; and S_{xy} is the magnitude of the power cross-spectrum of M_x and M_y. Coherence indicates the frequency distribution of correlation, thus its importance (in structural analysis) depends on the natural frequencies of the contributing modes of the building vibration.

Fig. 7 presents the cross-wind/along-wind, Fig. 7(a), cross-wind/torsional, Fig. 7(b) and along-wind/torsional, Fig. 7(c), coherences involving wind loading components on the same building. These coherences are denoted herein as the building coherences. The selected relative spacing of the buildings, indicated in parentheses, is associated with the highest magnitude of the correlation coefficient of a particular combination of the loading components. For comparison, the coherences obtained for a single building (SB) case are included. The shading in Fig. 7 (and in Fig. 8) indicates the range of the reduced frequency, 0.12 through 0.5, of interest in design of typical twin tall buildings.

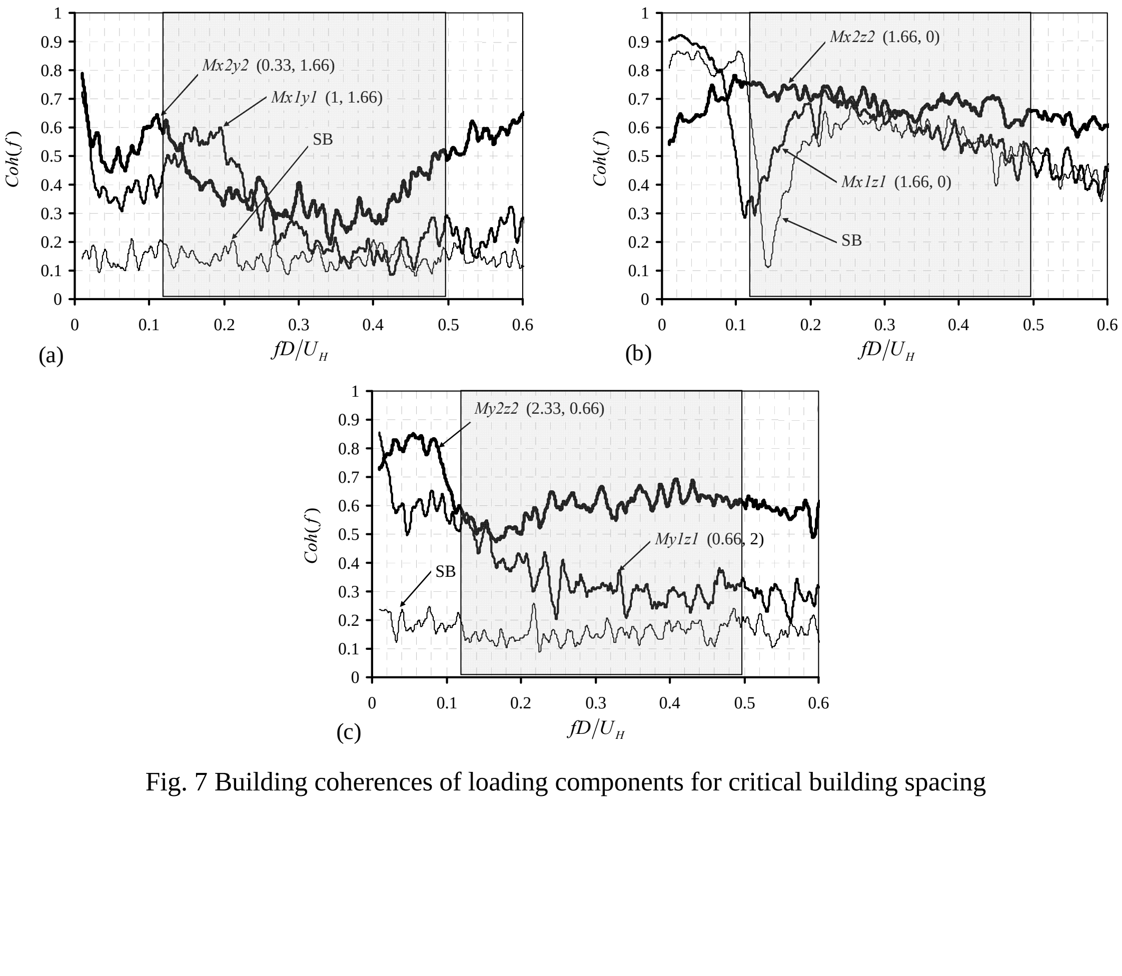


Fig. 7 Building coherences of loading components for critical building spacing

It can be seen in Figs. 7(a) and 7(c) that the cross-wind/along-wind and along-wind/torsional coherences were overall higher than those for the SB case. For the moderate to high reduced frequencies, the cross-wind/torsional coherences were similar to the coherence for the SB case, see Fig. 7(b). At low frequencies, a close agreement between the cross-wind/torsional coherences on the upstream building B1 (M_{x1z1}) and the SB case is noteworthy. In passing, it should be pointed out that coherences for the SB case, displayed in Fig. 7, are in agreement with those reported by other researchers (Tallin and Ellingwood 1985, Thoroddsen *et al.* 1988, and Ni *et al.* 2001).

These results show that in addition to high crosswind-torsional coherence, each of the two buildings (in close proximity) experiences enhanced along-wind/cross-wind and along-wind/torsional loading coherences. These coherences are negligible in the SB case.

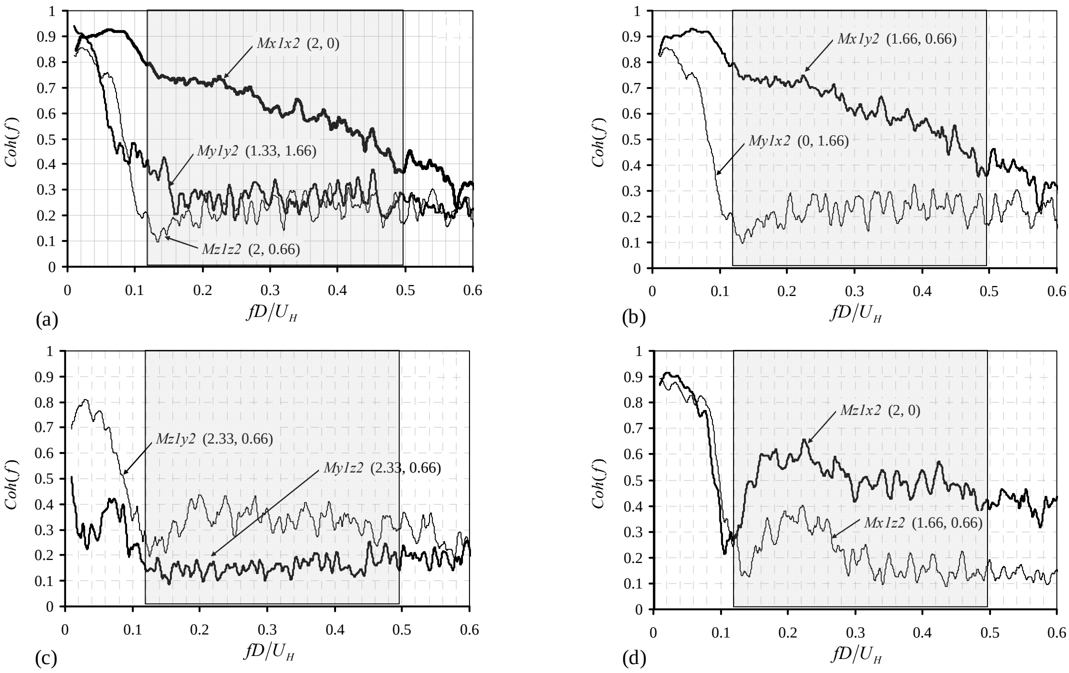


Fig. 8 Inter-building coherences of wind loading components for critical building spacing

4.5 Inter-building coherences

Fig. 8 shows the inter-building coherences – the coherences involving components of wind loading exerted on the two buildings. The selected locations correspond to the largest magnitudes of the correlation coefficients. It can be seen in Fig. 8(a) that the highest coherence of the same components exerted on the two buildings was obtained for the crosswind direction, while for the remaining directions (along-wind and torsional) the coherences were low.

The inter-building coherences involving pairs of wind components in different directions are shown in Figs. 8(b) through 8(d). The along-wind/cross-wind coherence, see Fig. 8(b), was significantly higher than that for the remaining wind loading combinations in Fig. 8. It is noteworthy that the frequency dependence of the cross-wind/torsional inter-building coherences in Fig. 8(d) was similar to that exhibited by the building coherence of the upwind building B1 (M_{x1z1}) and the SB case in Fig. 7(b).

The obtained correlation and coherence results are summarized in Table 1. The building and inter-building correlation coefficients and the average coherences are displayed, for locations of building B1 associated with the largest magnitude of the correlation coefficient indicated in Fig. 6. The coherence averaging was carried out over the frequency range shown shaded Figs. 7 and 8. It can be seen that the crosswind-torsional average coherences on each building (building coupling, M_{x1z1}, M_{x2z2}) were close to a conservative value of 0.7 assumed by Tallin and Ellingwood (1985) and Chen and Kareem (2005). For some building spacings, the inter-building average coherence was significant. The inter-building average coherences of similar components were moderate for the alongwind (0.28, M_{y1y2}) and torsional (0.22, M_{z1z2}) directions.

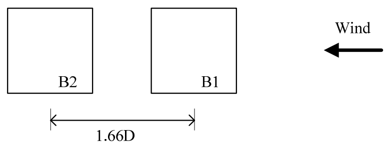
A high value (0.71) was observed for the crosswind direction (M_{x1x2}). The maxima of the inter-building average coherences involving different loading components were: 0.61 for the cross-wind/along-wind (M_{x1y2}), 0.33 for the torsional/along-wind (M_{z1y2}) and 0.51 for the torsional-crosswind (M_{z1x2}) directions.

Table 1 Summary of loading correlations and coherences for critical building spacings

Aerodynamic coupling		Loading components	Location (building B1)	Correlation coefficient (magnitude)	Coherence (average)
Building coupling	B1	M_{y1x1}	(1, 1.66)	0.45	0.3
		M_{x1z1}	(1.66, 0)	0.62	0.58
		M_{y1z1}	(0.66, 2)	0.54	0.34
	B2	M_{x2y2}	(0.33, 1.66)	0.37	0.37
		M_{x2z2}	(1.66, 0)	0.54	0.69
		M_{y2z2}	(2.33, 0.66)	0.66	0.59
Inter-building coupling		M_{x1x2}	(1.66, 0)	0.68	0.71
		M_{y1y2}	(1.33, 1.66)	0.83	0.28
		M_{z1z2}	(2, 0.66)	0.54	0.22
		M_{x1y2}	(1.66, 0.66)	0.55	0.61
		M_{y1x2}	(0, 1.66)	0.47	0.22
		M_{y1z2}	(2.33, 0.66)	0.63	0.16
		M_{z1y2}	(2.33, 0.66)	0.56	0.33
		M_{z1x2}	(2, 0)	0.53	0.51
		M_{x1z2}	(1.66, 0.66)	0.61	0.21

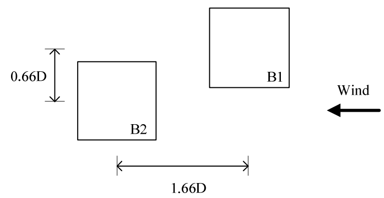
Based on the results in Tab. 1, two configurations of the overall highest average coherence were identified, see Fig. 9: (X/D, Y/D) = (1.66, 0.0) - two buildings aligned with the wind, and (X/D, Y/D) = (1.66, 0.66) - upwind building (B1) with an offset in the crosswind direction. The average coherences associated with these configurations are included in Fig. 9. The high level of the coherence ($\geq$ 0.45) is indicated using the boldface. As shown in Fig. 9(a), for the buildings aligned with the wind, the building and inter-building crosswind-torsional coherences were high ($\geq$ 0.5). A similar (high) level was exhibited by the inter-building coherences of the loading components in the same direction. The remaining coherences were low, not exceeding 0.17. The average coherences of the remaining critical configuration, listed in Fig. 9(b), indicated a similar level of coupling of wind loading for the upstream building (B1) and a stronger coupling for the downstream building (B2). The inter-building loading coupling was weaker than that for the wind-aligned configuration, in Fig. 9(a).

The above results indicate that significant building and inter-building coherences of wind loading exist within the frequency range of interest. The (implied) aerodynamic coupling depends on the relative position of the buildings. This coupling should be carefully examined during evaluation of wind effects on tall buildings in close proximity.



	*Mx*1	*My*1	*Mz*1	*Mx*2	*My*2	*Mz*2
*Mx*1	1	0.14	**0.58**	**0.71**	0.14	**0.49**
*My*1		1	0.14	0.15	**0.64**	0.15
*Mz*1			1	**0.58**	0.14	**0.52**
*Mx*2				1	0.14	**0.69**
*My*2	Symmetric				1	0.17
*Mz*2						1

(a)



	*Mx*1	*My*1	*Mz*1	*Mx*2	*My*2	*Mz*2
*Mx*1	1	0.36	**0.47**	**0.45**	**0.61**	0.21
*My*1		1	0.3	0.21	0.26	0.23
*Mz*1			1	0.36	0.37	0.2
*Mx*2				1	**0.55**	**0.55**
*My*2	Symmetric				1	**0.57**
*Mz*2						1

(b)

Fig. 9 Configurations of the highest average coherences

5. Conclusions

The findings of this study are summarized as follows:

(1) The alongwind loading was strongly coupled with the crosswind and torsional loadings induced on the same building of the twin building (TB) configuration. The observed correlation coefficients and the average coherences reached up to 0.66 and 0.59, respectively. These high values are in contrast with a case of an isolated building (SB).

(2) The crosswind-torsional correlation and coherence of loading on each building were approximately similar to those for the SB case. The maximum values of the correlation coefficient and the average coherence were 0.62 and 0.69, respectively.

(3) For some building spacings, the inter-building correlation (correlation involving wind loading components on the two buildings) was significant. The maxima of the inter-building correlation coefficient and the average coherence of similar components reached up to 0.83 and

0.71, respectively. For different loading components they were equal to 0.63 and 0.61, respectively.

(4) Ten configurations of high correlation coefficients of the wind loading components were identified. Examination of the average coherences associated with these configurations led to identification of two configurations of the strongest aerodynamic coupling: (a) two buildings aligned with the wind and (b) wind-aligned buildings with a crosswind offset of the upstream building.

(5) The discussed high correlations and coherences of the wind loading suggest that determination of wind loading on structurally connected tall twin buildings should include detailed mapping of coupling of the aerodynamic loading. This task can be accomplished using DHFFB or alternative experimental technique(s), e.g., a multi-channel electronically scanned pressure system.

(6) Systematic structural analyses are needed to investigate the impact of the correlations and coherences of specific wind loading components on the aerodynamic responses of tall buildings in close proximity.

(7) The presented results were not meant to be recommended for direct application in wind resistant design of tall twin buildings. They were intended to show that wind loading on tall buildings in close proximity is significantly different from that on single buildings and that it can be conveniently mapped using the DHFFB.

Acknowledgements

Partial financial support for the work described was provided by the Research Institute of Technology, Samsung Engineering & Construction. Laboratory assistance provided by Dr. Munehito Endo of WEFL at Colorado State University and constructive input by the reviewers of this paper are gratefully acknowledged.

References

Boggs, D.W. and Hosoya, N. (2001), “Wind-induced techniques to address structures with multiple coupled interactions”, *Proceedings of the Structures 2001 – A Structural Engineering Odyssey, Washington*, D.C., USA.

Chen, X. and Kareem, A. (2005), “Coupled dynamic analysis and equivalent static wind loads on buildings with three-dimensional modes”, *J. Struct. Eng. -ASCE*, **131**(7), 1071-1082.

Huang, P. and Gu, M. (2005),"Experimental study on wind-induced dynamic interference effects between two tall buildings", *Wind Struct.*, **8**(3), 147-161.

Lam, K.M., Leung, M.Y.H. and Zhao, J.G. (2008), “Interference effects on wind loading of a row of closely spaced tall buildings”, *J. Wind Eng. Ind. Aerod.*, **96**(5), 562-583.

Lim, J. and Bienkiewicz, B. (2007), “Wind-induced response of structurally coupled twin tall buildings”, *Wind Struct*., **10**(4), 383-398.

Lim, J., Bienkiewicz, B. and Endo, M. (2006), *Investigation of interference and coupling wind effects on tall buildings*, Technical Report Submitted to Samsung Corporation, Wind Engineering and Fluids Laboratory, Colorado State University.

Makino A. and Mataki Y. (1993), “Combination method maximum response in consideration of statistical correlation of wind forces acting on high-rise building: study on rectangular section models”, *Proceedings*

of the 1st IAWE European and African Regional Conference, Guernsey, UK.
Ni, Z.H., He, C.K., Xie, Z.N., Shi, B.Q. and Chen, D.J. (2001), "Experimental test on bridge jointed twin-towered buildings to stochastic wind loads", *Wind Struct*., **4**(1), 63-72.
Saunders, J.W. and Melbourne, W.H. (1979), "Buffeting effects of upstream buildings", *Proceedings of the 5th International Conference on Wind Engineering*, Fort Collins, CO, USA.
Tallin, A. and Ellingwood, B. (1985), "Wind induced lateral-torsional motion of buildings", *J. Struct. Eng. - ASCE*, **111**(10), 2197-2213.
Thoroddsen, S.T., Peterka, J.A. and Cermak, J.E. (1988), "Correlation of the components of wind-loading on tall buildings", *J. Wind Eng. Ind. Aerod.*, **28**(1-3), 351-360.
Xie, J. and Irwin, P.A. (2001), "Wind-induced response of a twin-tower structure", *Wind Struct.*, **4**(6), 495-504.