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The Role of Belt Wall in Minimizing The Response Due To Wind Load

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Abstract. Outrigger is one of the tall building structural systems that are used to reduce the building responses due to the wind. Outrigger is a stiff beam that connects the core wall to exterior columns and this enables the vertical shear to be transferred from the core to the external columns, thereby forcing the perimeter columns to participate in carrying the overturning moment due to the wind. Belt wall is often added to a building with outrigger system to further reduce the displacement and acceleration of a tall building having an outrigger system. However, it is not known how effective the belt wall is in further reducing the building responses. Thus, 64 story reinforced concrete buildings are studied in order to determine how the belt wall improves the building responses due to the wind. Buildings with an outrigger system and buildings with a combination of the outrigger and belt wall system are analysed by a structural engineering software in order to determine the natural frequencies and eigenvectors in the along-wind, across-wind and torsional direction. The along-wind responses are determined by employing the procedures from the ASCE 7-16 while the across-wind responses of the buildings are calculated based on the procedures and wind tunnel data available in a database of aerodynamic load. Results from the analysis show that the belt wall reduces the along-wind and across-wind responses slightly. However, belt wall reduces the torsional acceleration of the buildings significantly, which otherwise cannot be reduced by the outrigger system.

1 Introduction

Deflection and acceleration of tall buildings must be controlled as large deflection and high acceleration may cause discomfort to the building occupants. Deflection of more than 1/200 of the height of the buildings, for example, can result in improper drainage, impaired operation of doors and windows, and damage to lightweight partition [1]. Thus, the deflection cannot exceed a certain limit that has been specified by the local building authorities. The limit of drift index, which is the ratio of the maximum deflection at the top of the building to the total height is between 0.001 to 0.005 for different countries. The maximum total drift and inter-story drift of structure that is subjected to wind force allowed by Malaysian Code, MS 1553:2002 [2], is 1/500 and 1/750 of the height, respectively. Further, [3] recommended the drift limits of building to be between 1/600 to 1/400.

According to [4], human perception to motion and vibration is affected mainly due to acceleration. People can strongly perceive motion and have difficulty in walking naturally as well as losing balance while standing if the acceleration exceeds 0.4 m/s2 [5]. ASCE7-16 [6] specifies the need to control the structural motion by reducing both building and floor accelerations such that the discomfort of the occupants and the impairment of the equipment could be avoided. People in a quiet environment will be disrupted when the acceleration of nonstop vibrations is between 0.05g to 0.01g but those in a loud environment such as during events will be irritated only when the acceleration reaches 0.02 g to 0.05 g. Further, peak acceleration influences the perception of motion while comfort during continuous motion is related to RMS acceleration [7]. The occupant comfort in the building can also be evaluated based on the modal acceleration [8]. According to [9], the current design code of practice that applies perception threshold has failed to include other significant effects due to building motion such as sopite syndrome and work performance.

The structural response of the building can be reduced by employing alternative structural systems or passive and active control devices [10]. Belt wall and outriggers systems are tall building structural systems that can be employed to minimize the building responses caused by wind. An outrigger is a stiff beam that connects the core of high rise building to the peripheral columns. The existence of outrigger causes the emergence of tensile forces in the columns at the windward surface and compressive forces in the columns at the leeward surface when the building is subjected to lateral load [11]. According to [12], outriggers improves the building overturning stiffness and strength. Multiple

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outriggers can be constructed in building. [13] studied the effect of using four outriggers that were located at different height from the ground in reducing the lateral displacement due to the wind.

Belt wall is added to building with outrigger to mobilize the other peripheral columns other than those columns located at the ends of the outriggers in resisting the lateral load. Belt wall is a deep spandrel beam which can be either one or two stories that are constructed around the building at the same level as the outriggers. The 77-story Plaza Rakyat Office Tower in Kuala Lumpur, Malaysia utilizes core wall, perimeter frame, two belt walls and three outriggers to resist wind load [14]. Tower Palace III in Seoul Korea employs indirect outrigger belt wall system to control wind-induced response [15].

However, it is not known how effective the belt wall is in reducing further the responses of buildings with outrigger system. The objective of this research is to study the effectiveness of belt wall system in minimizing the building response (displacement and acceleration) to wind loading.

2 Properties of Building Models

Analysis was performed on a reinforced concrete building with a footprint of 48 m x 48 m square plan. The 288 m high building has 64 stories and is categorized as a flexible building due to the ratio of height to the horizontal dimension of the building exceeding 4:1 and its lowest natural frequency being less than 1 Hz. Fig.1 shows the typical plan of the building investigated.

The reinforced concrete core, columns, diagonal beams and perimeter beams used high strength concrete with strength of 80 MPa and modulus of elasticity 4.83 x 107 kPa. The 110 mm thick composite floor was supported by wide flange beams with section of UB 457 x 191 @ 98 kg/m, UB 610 x 229 @ 125 kg/m UB 610 X 305 @ 179 kg/m for core wall size of 12m x 12m, 18m x 18m and 24m x 24m, respectively, that span from the core wall to the perimeter beams.

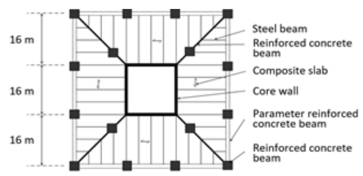

Fig. 1. Typical plan view of the building investigated.

Two thicknesses of core wall, which were 350 mm and 800 mm were used for each size of the core wall. The thickness of the core wall was constant throughout the height of the building. The internal columns which exist only in buildings with 12m x 12 m and 18 m x 18 m core wall had cross sections of 1300 mm x 1300 mm, 1100 mm x 1100 mm and 700 mm x 700 mm for floor 1 to 25, 26 to 50 and 51 to 64 respectively. The perimeter and diagonal beams had 300 mm x 1000 mm cross-section.

Three types of buildings were investigated: core wall, combination of core wall and outriggers and combination of core wall, outriggers and belt wall. Buildings with outriggers had four 400 mm wide and two-storey high outriggers that connected the corner of the core wall to the peripheral columns at the corner of the building at mid-height of the buildings. The belt wall used in this study was solid 350 mm wide and two storeys high reinforced concrete wall. white, and this should be taken into account when preparing them.

3 Methodology

The procedure of this project is as given below:

1. Model the building and analyse it by using the structural analysis and design software, GTSTRUDL in order to obtain the eigenvalues and eigenvectors of the building corresponding to along wind, across wind and torsional modes.
2. Compute the responses in the along wind direction by employing the equation given by the ASCE 7-16. Data such as the dimensions, frequency and mass of the building; wind speed and type of terrain are required to execute the along-wind response.
3. Execute the across wind and torsional responses. The value of CM, non-dimensional moment coefficient and σ_M, root mean square of the fluctuating base moment was obtained from an interactive aerodynamic database of the University of Notre Dame, U.S.A. columns at the top or the bottom of the page.

3.1 Modeling of the Building

Space frame members were used to model all columns and beams. Meanwhile, isoparametric quadratic solid (IPQS) elements that have 20 nodes each, were used to model the core walls, outriggers and belt walls. Each node of the IPQS element has three degrees of freedom, which are displacements: u1, u2, u3, Fig.2 shows the models of outrigger building system and combination of belt wall and outrigger system used for the eigenproblem analysis which was performed by GTSTRUDL structural analysis software to obtain the natural frequency in the along-wind, across-wind, and torsional directions, as well as the eigenvectors in the across-wind direction.

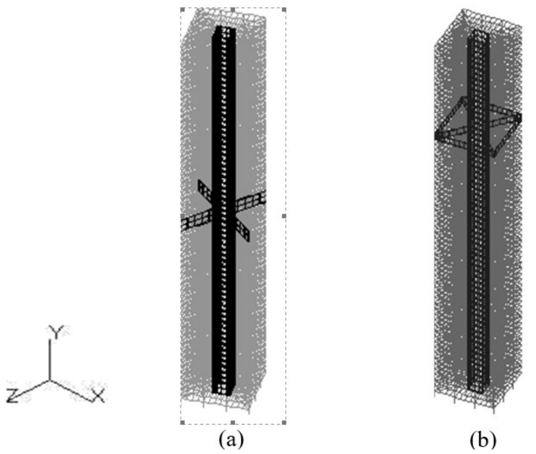

Fig. 2. (a) Outrigger and core wall system; (b) Beltwall, outrigger and core wall system

3.2 Wind Speed

Wind speeds in three wind environment: Malaysia, New York and Hong Kong were used in this investigation. Malaysia which experiences thunderstorms and monsoonal winds has benign wind environment. Both New York and Hong Kong have aggressive wind environment. New York is exposed to hurricane whilst Hong Kong is exposed to typhoon. The 3-second gust wind speed for 50 year return period at 10 m height is 33.5 m/s (MS 1553:2002) in Kuala Lumpur and 49 m/s in New York (ASCE 7-16). Hong Kong has 3-second gust wind speed for 50 year return period of 68 m/s at 50 m height (Hong Kong Code of Practice) [16].

Along-wind responses were determined by utilizing the formulation given in ASCE 7-16 where 3-second gust wind speeds for 10-year return period at 10 m height in open terrain was used. The 3-second gust wind speeds for 10-year return period at 10 m height in open terrain for Malaysia, New York and Hong Kong wind environment were 28.14 m/s, 36.26 m/s and 42.48 m/s, respectively. Meanwhile, one-hour averaging time wind speeds for 10-year return period at building height in urban area was used in the calculation of the across-wind and torsional responses which utilized the procedure outlined in the aerodynamic database in the University of Notre Dame. The 3-second gust wind speed at 10 m height was converted to the wind speed at the building height by using the power law and then was converted to one-hour averaging time by using the curve given in ASCE7-16. The wind speeds were 25.27 m/s, 32.56 m/s and 38.14 m/s for Malaysia, New York and Hong Kong wind environment, respectively.

3.3 Along-Wind Response Positioning

The natural frequency and the wind speed were needed to calculate the along-wind displacement and acceleration by employing closed form equation provided in the ASCE7-16. The maximum along-wind displacement Xmax(z) as a function of height above the ground surface is given by

$$X_{\max}(z) = \frac{\phi(z)\rho b h C_f \hat{V}_{\bar{z}}^2}{2m_1(2\pi n_1)^2} KG \quad (1)$$

where $\phi(z)$ = fundamental mode shape = $(z/h)^{\xi}$; ξ = mode exponent; ρ = the air density; C_f = mean along-wind force coefficient; m_1 = modal mass = $\int \mu(z)\phi^2(z)dz$; $m_1\mu(z)$ = mass per unit height; $K = 1.65\hat{\alpha}/(\hat{\alpha}+\xi+1)$; $\hat{V}_{\bar{z}}$ = the 3 sec gust speed at height $\bar{z} = \hat{b}(z/33)^{\hat{\alpha}}\hat{V}_{ref}$, $\hat{V}_{ref}$ = 3 s gust in exposure C at reference height; G_f = gust factor; n_1 = building natural frequency in Hz. The maximum along-wind acceleration as a function of height above the ground surface is given by

$$\ddot{X}_{\max}(z) = g_{\ddot{x}}\sigma_{\ddot{x}}(z) \quad (2)$$

where $\sigma_{\ddot{x}}(z)$ = rms along-wind acceleration as a function of height above the ground surface; $g_{\ddot{x}} = \sqrt{2\ln(n_1T)} + \frac{0.5772}{\sqrt{2\ln(n_1T)}}$ and T = 3600 seconds

3.4 Across-Wind and Response

Both of the across-wind and torsional responses computed in this project were based on the aerodynamic database of the University of Notre Dame that can be accessed at the URL address http://www.nd.edu/~nathaz/. The database stores the non-dimensional moment coefficient, CM which was calculated based on the results from the wind tunnel test of different models. The models had different cross sections which were rectangular with different width to depth ratio, triangular and parallelogram. Three different heights (406 mm, 508 mm and 610 mm) for each type of cross section were used. These rigid balsa wood models were tested in an 18 m long boundary layer wind tunnel with a 3 m x 1.5 m cross-section [17]. The upstream spires together with the surface roughness that was added to the tunnel floor create the required boundary layers in the wind tunnel. The dynamic structural loads of models due to the wind in boundary layers of open terrain and urban area were determined by using a high-frequency multicomponent force balance [18]. Measurement was made at a rate of 300 Hz for a 5-minute duration. Fast Fourier transform was applied to obtain the spectra which were ensemble averaged.
The calculation of torsional acceleration requires the values of the radius of gyration of the building while the computation of the across-wind displacement requires eigenvectors and lumped mass at selected points. Only the maximum across-wind and torsional acceleration which occur at the top of the building, are computed. white, and this should be taken into account when preparing them.

4 Results And Discussion

The results from the analysis show that the reduction of the along-wind responses due to the addition of the belt wall to a building which already has an outrigger system is less than the reduction of the along-wind response when the outriggers system is added to a building which has no outrigger at all (Fig. 3 and 4). The reduction of the across-wind responses due to the wind in all the three wind environment: Malaysia, New York and Hong Kong when belt walls are added to the buildings with the outrigger system is less than the reduction of the across-wind responses when the outrigger system is added to a building which has no outrigger at all. Fig. 5 plots the histograms of the across-wind responses that correspond to Hong Kong wind environment.

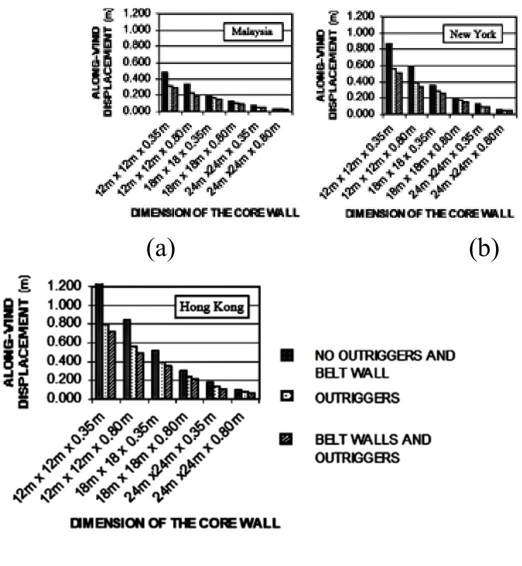

Fig. 3. Comparison of the value of the along-wind displacement for a building with two-storey deep outriggers and a building with both two-storey deep outriggers and belt walls in (a) Malaysia, (b) New York and, (c) Hong Kong wind environment.

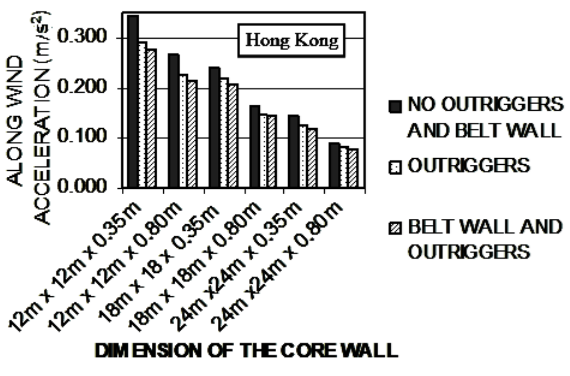

Fig. 4 Comparison of the along-wind acceleration of a building with two-storey deep outriggers and a building with both two-storey deep outriggers and belt walls in Hong Kong wind environment.

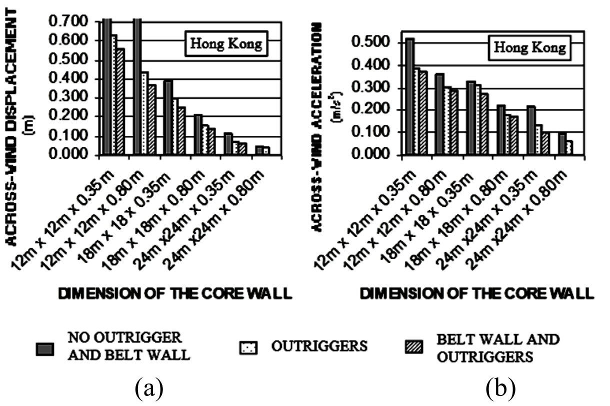

Fig. 5 Comparison of the (a) across-wind displacement (b) across-wind acceleration of a building with no outriggers, two-storey deep outriggers and with both two-storey deep outriggers and belt walls in Hong Kong wind environment.

Interestingly, the torsional response of the building remained the same when the outriggers system was added to the building. However, when belt wall was added to a building with outrigger system, the torsional response of the building reduced significantly as shown in Fig. 6. This is due to the increment of the natural frequency in the torsional mode which was caused by the increment of the torsional stiffness of the building due to the addition of the belt wall. Table 1 tabulates the values of torsional stiffness constant, *K*, for the core wall, outrigger and belt wall. The *K* value is the same for all belt walls as the dimension of the belt wall is the same for all the buildings no matter what the dimension of the core wall is (Fig. 7). Table 1 also shows the value of the natural frequency for the building with core wall and a combination of outriggers and core wall is the same for the torsional mode due to the small contribution of the *K* values by the outriggers to the original building with core wall only. On the other hand, the sudden increment of the natural frequency in the torsional mode due to the addition of the belt wall is caused by the large value of *K* of the belt wall that was added to the original building system

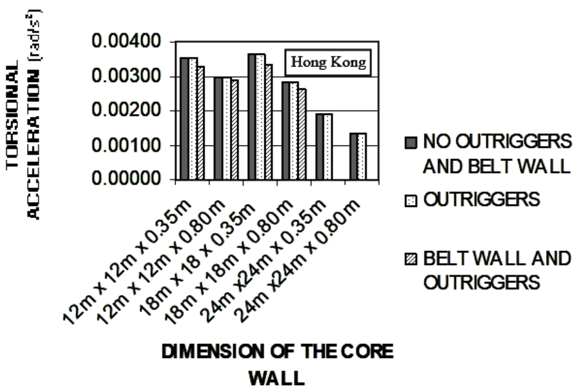

Fig. 6. Comparison of the value of the torsional acceleration of a building with no outriggers, two-storey deep outriggers and a building with both two-storey deep outriggers and belt walls in Hong Kong wind environment.

Table 1. Comparison of the *K* or torsional stiffness constant values of the core wall, outrigger and belt wall elements, and the natural frequency in torsional mode of the building with belt wall and no belt wall.

CORE WALL SIZE (M X M xM)	*K* VALUES OF THE CORE WALL (NM)	*K* VALUES OF THE OUTRIGGER (NM)	*K* VALUES OF THE BELT WALL (NM)	NATURAL FREQUENCY IN TORSIONAL MODE		
				BUILDING WITH CORE WALL ONLY (HZ)	BUILDING WITH CORE WALL, OUTRIGGER (HZ)	BUILDING WITH CORE WALL, OUTRIGGER AND BELT WALL (HZ)
12 x 12 x 0.35	553.408	34.412	38225.37	0.145	0.145	0.170
18 x 18 x 0.35	1924.430	28.619	38225.37	0.173	0.173	0.192
24 x 24 x 0.35	4629.792	22.826	38225.37	0.281	0.281	0.309

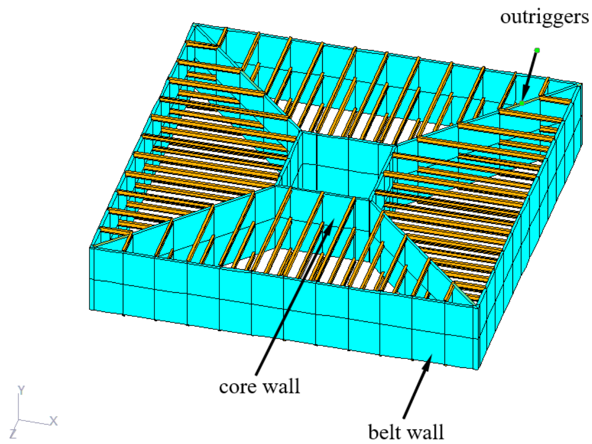

Fig. 7 A view of a floor where the belt wall is located.

4 Conclusion

The purpose of conducting the study on the belt wall system is to find out how the addition of the belt walls improves the responses of a building which already built with the outrigger system. The addition of belt walls to a building that already has the outrigger system will reduce slightly the responses in the along-wind and across-wind direction. In contrast, the torsional acceleration which otherwise could not be reduced when only the outriggers are added to the core wall system is reduced significantly when the belt wall is added to the buildings with the outrigger system. As a conclusion, belt wall is effective in reducing the torsional acceleration but is not so effective in reducing the along-wind and across-wind responses.

Furthermore, allowing perforation of the belt wall will allow the floor where belt wall is located for usage other than as a mechanical floor as commonly practiced. Thus, it is suggested that a study of buildings that have belt wall system with perforation to be performed in order to understand its effectiveness in reducing the building responses due to the wind.

References

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Table 1. Setting Word's margins.

Margin	**mm**
Top	25
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	Font	Spacing	numbering
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subsection	10-point **Arial bold**	6 mm before 3 mm after	1.1, 1.2, 1.3, etc.
subsubsection	10-point *Arial Italic*	6 mm before 3 mm after	1.1.1, 1.1.2, 1.1.3, etc.

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Equations should be centred and should be numbered with the number on the right-hand side.

$$T_s\,(l,t) = T_g\,(l,t) \quad (1)$$

$$T_s\,(l,t) = T_g\,(l,t)\ T_b\,(x \rightarrow -\beta,\, t) = 0 \quad (2)$$

Use italics for variables (u) and bold ($\mathbf{u}$) for vectors. The order for brackets should be {[()]}, except where brackets have special significance.

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Book title, Proceedings title	Italic
Volume number	Bold
Page number	Normal
Year	Normal In brackets

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