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THE ROLE OF AERODYNAMIC MODIFICATIONS IN THE FORM OF TALL BUILDINGS AGAINST WIND EXCITATION

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Modern tall buildings go higher and higher with the advances in structural design and high strength materials. However, every advance in height comes with a new difficulty. Efficient structural systems, high strength materials, and increased height, result with decrease in building weight and damping, and increase in slenderness. On the other hand, as the height and slenderness increase, buildings suffer from increased flexibility, which has negative effects in wind loading. Flexible structures are affected by vibration under the action of wind which cause building motion, and plays an important role in the structural and architectural designs. Understandably, contemporary tall buildings are much more vulnerable to wind excitation than their predecessors. Hence, different design methods and modifications are possible in order to ensure the functional performance of flexible structures and control the wind induced motion of tall buildings. An extremely important and effective design approach among these methods is aerodynamic modifications in architecture. In this context, the authors classify these aerodynamic modifications in architecture for resisting the lateral loads. Wind safe tall building design begins with the architect, and the influence of the wind action must be taken into consideration from the very beginning of the architectural design process by considering building aerodynamics.

INTRODUCTION

The race to build the tallest introduces new obstacles to today's architects and engineers. Each step to the sky by means of the tallest buildings forces the designers to find innovations to overcome the newly emerging obstacles. One of the greatest problems of today's tall buildings is their vulnerability to environmental excitations such as wind leading to horizontal vibration.

Thanks to the advent of high strength and lightweight materials, contemporary tall buildings are remarkably much more slender and lighter than their former precedents. On the other hand, these improvements are often accompanied by increased flexibility and lack of sufficient inherent damping. Such undesired conditions cause serious problems especially for the occupants of the building. Under the action of wind and excessive vibration, serviceability and occupant comfort are under a great threat. Even though the structure still carries satisfactorily all the lateral loads, it must satisfy the serviceability requirements as occupants' discomfort feeling - like dizziness, headaches, nausea - resulting from the lateral motion of the building.

Many researches and studies have been done in order to mitigate such an excitation and to improve the performance of tall buildings against wind loads (Kareem, Kijewski and Tamura, 1999). Different design methods and modifications are possible, such as some alternative structural systems and addition of damping systems in order to ensure the functional performance of flexible tall structures in terms of wind induced motion control.

Some aerodynamic modifications in architectural design are one of the effective design approaches which can significantly reduce the effect of the lateral wind force and thus, the building motion. Basically, these modifications are the tapered cross section, setback, sculptured top, modifications to corner geometry, and addition of openings through-building (Kareem, Kijewski and Tamura, 1999). By changing the flow pattern around the building, aerodynamic modifications in building shape, i.e. an appropriate choice of building form, moderates wind responses when compared to original building shape. As far as wind loading and resulting motions are concerned, for tall and slender buildings, the shape is critical and a governing factor in the architectural design. Understandably, tall building design requires a unique collaboration particularly between the architect and the engineer. This interdisciplinary approach to resolving building planning, construction, and usage issues plays a vital role. Moreover, wind safe tall building design begins with the architect, and so, the influence of the wind action must be considered from the very beginning of the architectural design process. Therefore, skyscrapers of the next generation will be the products of a collaboration, in particular between the architectural, structural and aerospace engineering fields without victimizing the architectural design.

WIND EXCITATION

The motion of tall buildings occurs primarily in three modes of action: along wind, across wind, and torsional modes. For a rectangular building with one face nearly perpendicular to the mean flow, the motion is measured in the along wind and across wind directions as well as in the torsional mode (Cho, 1998). In this context, along wind motion, across wind motion, and vortex-shedding phenomenon resulting from these motions were discussed and aerodynamic modifications against these motions were investigated.

Along wind motion: Along wind or simply wind is the term used to refer to drag forces (Taranath, 1998). Under the action of the wind flow, structures experience aerodynamic forces including also the drag (along wind) force acting in the direction of the mean wind (**Figure 1**). The structural response induced by the wind drag is commonly referred to as the along wind response. The along wind motion primarily results from pressure fluctuations on windward (building's frontal face that wind hits) and leeward face (back face of the building).

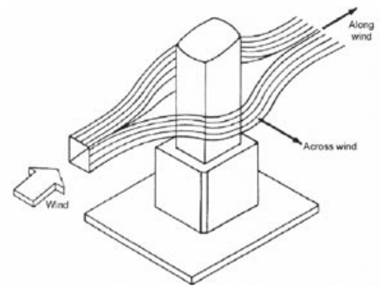

Figure 1. Simplified two-dimensional flow of wind (Taranath, 1998).

Across wind motion: The term across wind (**Figure 1**) is used to refer to transverse wind. The across wind response, is a motion in a plane perpendicular to the direction of wind. In the design of most modern tall buildings, the across wind response often dominates over the along wind response (Kwok, 1982). For instance, the wind tunnel test of the Jin Mao Building showed that its maximum acceleration in across wind direction at its design wind speed is about 1.2 times of that of the in along wind direction (Gu and Quan, 2004).

Buildings are very sensitive to across wind motion, and this sensitivity may be particularly apparent as the wind speed increases (Taranath, 1998). Wind induced instabilities of modern tower-like structures with excess slenderness, flexibility and lightly-damped (insufficient mechanical preventions against sidesway such as use of tuned mass dampers) features could cause considerably larger across wind responses. Besides, while the maximum lateral wind loading and deflection are usually observed in the along wind direction, the maximum acceleration of a building loading to possible human perception of motion or even discomfort may occur in across wind direction (Taranath, 1998).

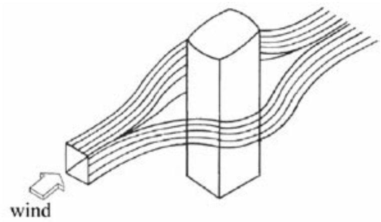

Figure 2. Simplified wind flow (Ilgın, 2006).

Vortex-shedding phenomenon: When a building is subjected to a wind flow, the originally parallel wind stream lines are displaced on both transverse sides of the building (**Figure 2**), and the forces produced on these sides are called vortices.

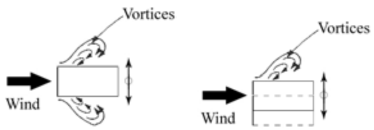

Figure 3. Vortices in different wind speed conditions: (a) vortices in low speed of wind (there is no vibration in the across wind direction); (b) vortices in high speed of wind – vortex-shedding phenomenon (there is vibration in the across wind direction) (Ilgin, 2006).

At low wind speeds, the vortices are shed symmetrically (at the same instant) on either transverse side of the building (**Figure 3a**), and building does not vibrate in the across wind direction.

On the other hand, at higher wind speeds, the vortices are shed alternately first from one and then from the other side. When this occurs, there is an impulse both in the along wind and across wind directions. The across wind impulses are, however, applied alternatively to the left and then to the right. This kind of shedding which causes structural vibrations in the flow and the across wind direction is called 'vortex-shedding', a phenomenon well known in fluid mechanics (Taranath, 1998). This phenomenon of alternate shedding of vortices for a rectangular tall building is shown schematically in **Figure 3b.**

AERODYNAMIC MODIFICATIONS AGAINST WIND EXCITATION

Many studies in the literature (Ali and Armstrong, 1995; Baker, 2004; Dutton and Isyumov, 1990; Hayashida and Iwasa, 1990; Holmes, 2001; Irwin, 2006; Isyumov, Fediw, Colaco and Banavalkar, 1992; Kareem and Tamura, 1996; Kawai, 1998; Kim and You, 2002; Kwok, 1988; Kwok, 1995; Kwok, William and Wilkie, 1988; Schueller, 1977; Schueller, 1990; Shimada and Hibi, 1995) show that from the wind engineer's point of view, aerodynamic modifications of tall building's form and cross-sectional shape are very effective design dimensions to be considered to control wind excitation and many of the most elegant and notable buildings utilize these approaches.

In this research, the following classification is proposed for the aerodynamic modifications of tall buildings against wind excitation:

1. Major architectural modifications: Modifications having effect on the architectural concept such as tapering, setbacks, sculptured building tops, varying the shape, openings.

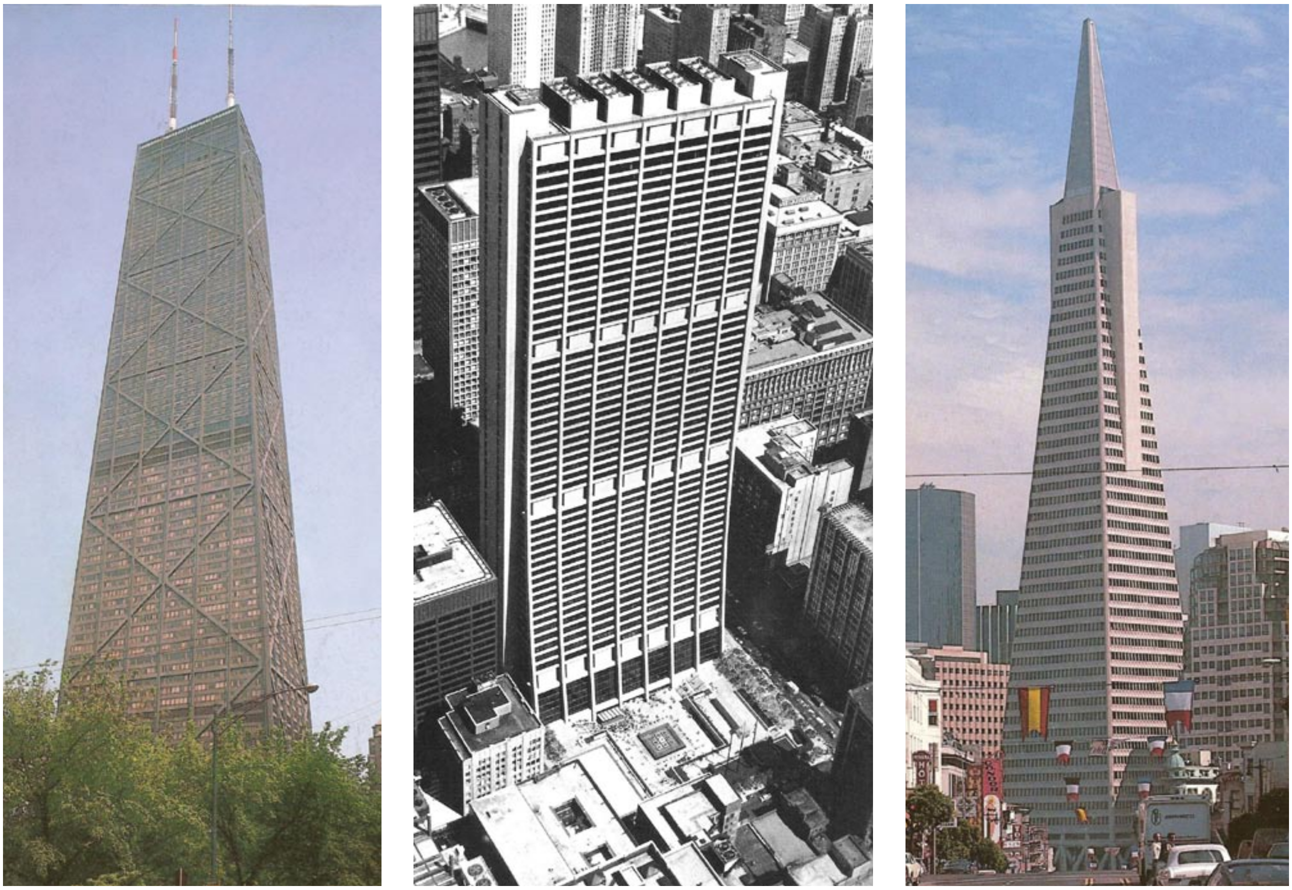

Figure 4. The examples of tapering effect utilization; (a) The John Hancock Center, (b) Chase Tower, (c) The Transamerica Pyramid.

2. Minor architectural modifications: Architectural modifications having no effect on architectural concept such as corner modifications and orientation of building in relation to the most frequent strong wind direction.

These are discussed below with examples.

The John Hancock Center (Chicago, 1969), Chase Tower (Chicago, 1969) and the Transamerica Pyramid (San Francisco, 1972) (**Figure 4**) are the examples of the 'tapering' effect utilization by creating smaller surface areas at higher levels and reducing the upper level plans, and thus mitigating the wind load (Ali and Armstrong, 1995; Schueller, 1977).

The Jin Mao Building (Shanghai, 1998) and the Petronas Towers (Kuala Lumpur, 1998) (**Figure 5**) use 'setbacks' to slightly taper the building shape, and 'sculptured building tops' highlighting the height of the structure, but also serving for the practical aerodynamic purposes such as reduction in the wind response of the building (Kareem and Tamura, 1996; Shimada and Hibi, 1995). The more sculptured a building's top, the better it can minimize the along wind and across wind responses, as proved in these examples (Kareem, Kijewski and Tamura, 1999).

While reducing the plan areas at the upper level by 'varying the shape' of the building along its height, minimizes the wind forces by causing the wind to behave differently, preventing it becoming organized as in the Burj Dubai Tower (UAE, 2008; **Figure 6**) (Baker, 2004). The Sears Tower (Chicago, 1974) is also a good example for this effect (**Figure 7**).

It is a well known fact that the shape of structures has a considerable effect on maintaining the lateral resistance. If the form of a tall building is limited to rectangular prisms, from geometrical point of view, this form is rather susceptible to lateral drift. Other building shapes such as cylindrical, elliptical, crescent, triangular and like, are not as vulnerable to lateral force action as a rectangular prism (Ali and Armstrong, 1995). Since these shapes have inherent strength in their geometrical form, they provide higher structural efficiency or allow greater building height at lower cost. Building codes permit a reduction of the wind pressure design loads for circular or elliptical buildings by 20 to 40% of the usual values for comparably sized rectangular buildings (Schueller, 1977). Hence, in many of the most famous buildings, these aerodynamically favorable forms are preferred. The Marina City Towers (Chicago, 1964; **Figure 8**) with its cylindrical form, the Millennium Tower (Tokyo, 2009; **Figure 9**) with tapered circular plan, Toronto City Hall (Toronto, 1965; **Figure 10**) with its crescent form, and the U.S. Steel Building (Pittsburgh, 1970; **Figure 11**) with its triangular plan are among these buildings (Ali and Armstrong, 1995; Shimada and Hibi, 1995).

Some modifications on cross-sectional shape such as slotted, chamfered, rounded corners, and corner cuts on a rectangular building (**Figure 12**), can have significant effects on both along wind and across wind responses of the building to wind (Kwok, 1995) as in Taipei 101 (Taipei, 2005; **Figure 13**). Corner modifications in Taipei 101 provide 25% reduction in base moment when compared to the original square section (Irwin, 2006). Chamfers of the order of 10% of the building width, makes 40% reduction in the along wind response, and 30% reduction in the across wind response when compared to the rectangular cross sectional shape without corner cuts (Holmes, 2001). Excessive rounding of corners of the cross section, approaching a circular shape in the cross section, and cylindrical form in the building, significantly improve the response against wind (Kareem, Kijewski and Tamura, 1999). In the study of Davenport (1971), peak deflection of the model in circular cross-section was about half of the one with square cross section where the building models were representative of roughly 70 storey structures.

Addition of openings completely through the building, particularly near the top, is another very useful way of improving the aerodynamic response of that structure against wind by reducing the effect of vortex shedding forces which cause across wind motion. The Shanghai World Financial

Figure 5. The examples of setbacks and sculptured building top utilization; (a) The Jin Mao Building, (b) The Petronas Towers.

Figure 6. The Burj Dubai (UAE, 2008).

Figure 7. The Sears Tower (Chicago, 1974).

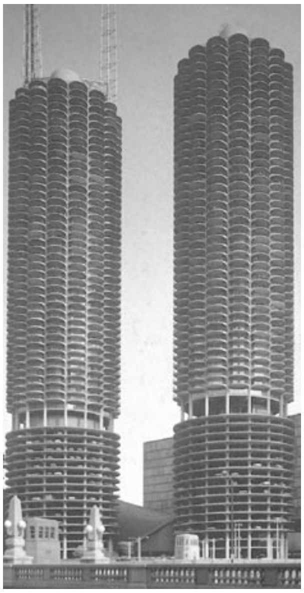

Figure 8. The Marina City Towers (Chicago, 1964).

Figure 9. The Millennium Tower (Tokyo, 2009).

Figure 10. Toronto City Hall (Toronto, 1965) .

Figure 11. The U.S. Steel Building (Pittsburgh, 1970).

Center (Shanghai, 2008; **Figure 14**) is a good example for this modification (Dutton and Isyumov, 1990).

DISCUSSION AND CONCLUSIONS

Tall buildings are gigantic projects demanding incredible logistics and management. They influence building industry, national economy, and require enormous financial investment. A careful coordination of the structural elements and the shape of a tall building which minimizes the lateral displacement, may offer considerable savings.

The problem of excessive building motions and their effect on comfort of the occupants can be a more difficult one to solve in the case of very tall and slender buildings. Structural measures alone are sometimes inadequate in finding a practical solution to motion problems and other approaches such as special damping devices must be used in such situations. As a result, an appropriate choice of building shape can result in a significant reduction of aerodynamic forces by changing the flow pattern around the building. This way of treatment can moderate wind responses when compared to original building shape. From the wind engineer's point of view, aerodynamic modifications such as setback, tapering, sculptured building tops, corner modifications, and addition of openings completely through the building are very effective design methods of controlling wind excitation. Aerodynamic modifications can significantly mitigate wind excitation of tall buildings, but can not eliminate them totally, and additional preventions like 'tuned mass damper' may be needed.

On the basis of wind tunnel tests on tall buildings available in literature, it is obviously noticed that some aerodynamic modifications can significantly mitigate wind excitation of tall buildings. The suggested modifications in this paper are advisable and thought to be used as assistive design tools. If an architect takes these facts into consideration, no or less modification will be needed at wind tunnel testing stage.

Figure 12. Corner modifications.

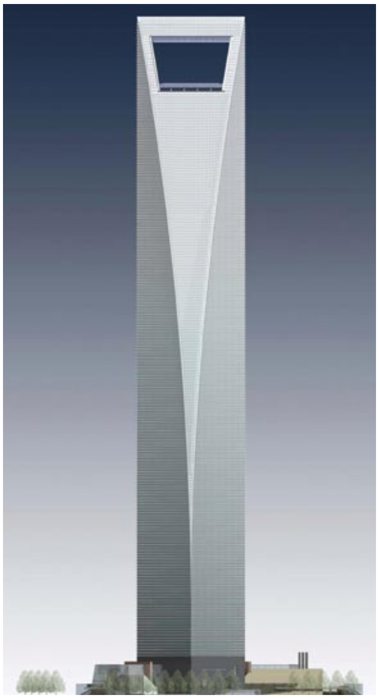

Figure 13. Taipei 101 (Taipei, 2005).

Figure 14. The Shanghai World Financial Center (Shanghai, 2008).

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Anahtar Sözcükler: yüksek bina; rüzgar etkisi; aerodinamik iyileştirme; rüzgar güvenli tasarım.

YÜKSEK BİNALARIN FORMUNDA RÜZGAR ETKİSİNE KARŞI YAPILAN AERODİNAMİK İYİLEŞTİRMELERİN ROLÜ

Modern yüksek binalar, yapı tasarımı ve yüksek mukavemetli malzeme alanlarındaki gelişmelerle daha da yukarıları zorlamaktadır. Diğer taraftan, yükseğe çıkıldıkça beraberinde getirdiği bazı zorlukların da aşılması gerekmektedir. Yapı sistemlerindeki yenilikler, yüksek mukavemetli malzemeler ve artan yükseklik sonucu, yapı ağırlığı ve salınım sönümü azalır ve yapı narinliği artar. Yapı yüksekliği ve narinliğinin artmasıyla artan yapı esnekliği, binalardaki rüzgar yükünü olumsuz yönde etkiler. Esnek yapılar, rüzgarın yarattığı titreşimden, salınım yoluyla etkilenir ve bu husus yapı ve mimarı tasarımda önemli rol oynar. Anlaşılacağı üzere, günümüz yüksek yapıları, öncüllerine göre rüzgar etkilerine daha hassastırlar. Bundan dolayı, esnek yapıların rüzgar etkilerinden dolayı salınımlarını kontrol altına almak için çesitli tasarım metodları ve iyileştirmeleri gündemdedir ve mümkündür. Mimarideki aerodinamik iyileştirmeler bu metodların arasında yer almaktadır. Buradan anlaşılacağı üzere, rüzgar güvenli bina tasarımı mimardan başlar ve rüzgar etkisini azaltmak için bina aerodinamiğini dikkate alarak yapılacak olan mimari tasarım gerek yapısal, gerekse bina kullanıcıları açısından önemli bir rol oynar. Bu bağlamda yazarlar, rüzgar yüklerine karşı mimaride uygulanabilecek aerodinamik iyileştirmeleri tartışmış ve sınıflama yoluna gitmiştir.