Design of sport stadia: wind action perspective

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ABSTRACT: This paper presents a review of the most relevant issues related to the structural and architectural design of large sport stadia, with the particular concern of wind loading aspects of these types of structures. The role and relevance of wind-tunnel tests of such facilities are highlighted. The paper summarises the wind engineering inputs in preparation for the 2010 FIFA World Cup tournament in South Africa however it is also relevant to the forthcoming 2012 European FIFA event in Poland and Ukraine.

1 BACKGROUND

1.1 *Soccer events in Poland and South Africa*

Significant international sports events, like the Olympic Games, athletic championships or soccer tournaments, became catalysts for the development of large magnitude modern sport facilities. Such an expansion programme recently took place in South Africa (Gizejowski & Goliger 2009), in preparation of 2010 FIFA World Cup tournament. It included the development and re-development of 13 stadia, each with a capacity of at least 40 thousand spectators. Poland is currently in the process of fast-tracking design and construction of 4 new stadia to host the 2012 European FIFA Cup. Both countries were (and are) faced with significant challenges in terms of the design and construction of these facilities.

1.2 *Design of modern stadia*

Due to the ever increasing competitiveness of sporting events, the designs of all modern sports facilities are governed by the provision of optimal conditions for the athletes / players. In most cases this necessitates measures to reduce negative external environmental effects (e.g. exposure to sun or rain), and furthermore, it often implies the introduction of enclosed or semi-enclosed roofs and façades.

Traditionally, for large-span structures the main drivers in formulating their form were related to the structural engineering limitations and the consequent feasibility regarding the weight and costs of elements. This paradigm has changed due to the recent development and use of modern lightweight materials and elements (e.g. cable roofs, spatial trusses or fabric membranes) which are often integrated in a structurally innovative (unorthodox) manner. An example of this is presented in Figure 1, which depicts the roof of the Port Elizabeth stadium, in South Africa, which combines intermittently, aluminum sheeting and fabric.

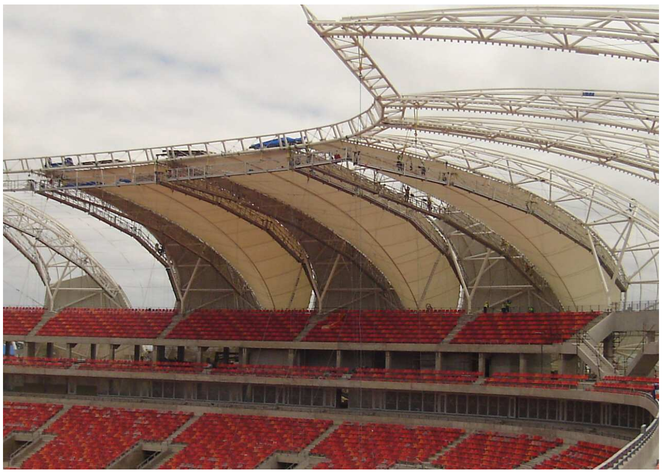

Figure 1. Construction of the Port Elizabeth stadium.

The overriding factors affecting the modern design criteria are heavily centered at the provision of an optimal spectacle, unobstructed view of the game and comfort of the players and spectators. Furthermore (in view of some tragic crowd panic events which have taken place in at several facilities across the world), this is followed by critically important issues related to the accessibility, fire safety and crowd control aspects.

Finally, functionality issues became important as most of the modern sport venues are designed as multi-purpose facilities, with some designed to be partially deconstructed with their elements to be re-erected at smaller satellite facilities.

All the above trends resulted in a substantial shift of the structural design paradigm in order to provide functional and safe public facilities.

2 STRUCTURAL DESIGN ASPECTS

2.1 *Structural systems*

There is huge diversity in the design of modern sport stadia across the world, and it is not possible to discuss this topic comprehensively in the current paper. A common denominator in the roof designs is the use of steel, although some stadia utilise shell-design principles, combined with the use of thin concrete.

Low-capacity stadia often comprise of beams (or trusses/girders) and columns positioned in front of the grandstand. Modern large stadia typically provide an unobstructed view by utilising cantilever roofs of various forms. Such roof structures were designed for the Mbombela stadium in Nelspruit, South Africa (Figure 2) or the proposed Baltic Arena in Gdansk, Poland (Figure 3).

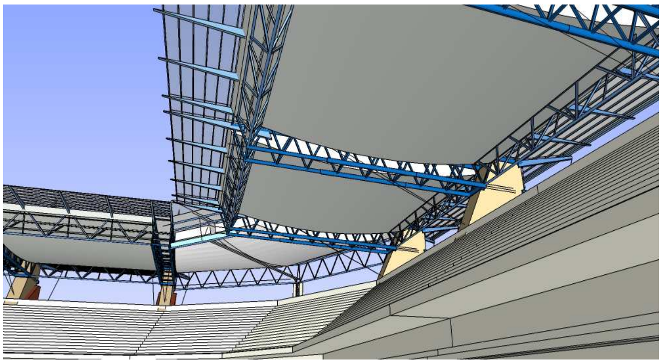

Figure 2. Roof of Mbombela stadium (courtesy of Goba Eng.)

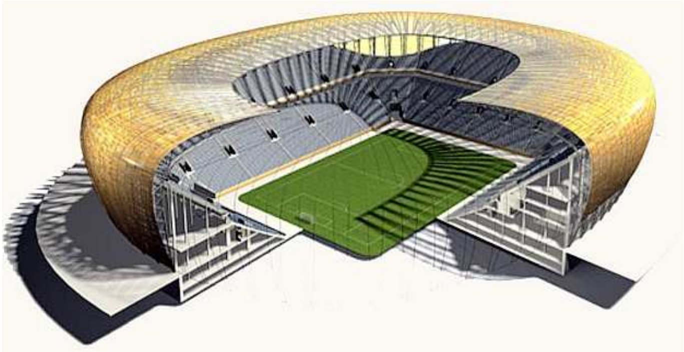

Figure 3. Proposed Baltic Arena in Gdansk (www.murator.pl).

‘Goal post’ structures are based on a frame or an arch positioned along the grandstand. This type of construction consists of a single-span beam or arch supported by columns placed at the ends of grandstands. Secondary systems, that span transversely to support the roof cover, are often suspended on the main arches. Such systems have been utilised at the Athlone Stadium in Cape Town and also at the Hong-Kong stadium (Figure 4).

Figure 4. Hong Kong Stadium (www.sporttours.com.au).

In cases where fabric membranes are utilised for roof coverage, the most popular and beneficial structural system is a compression-ring suspended-cable structure. Typically a rigid ‘outer’ ring is connected with an ‘inner’ cable ring at two levels. The Green Point in Cape Town and the Warsaw National stadia (Figure 5) are examples of this type of structural system.

Figure 5. Proposed National Stadium in Warsaw (www.stadionnarodowy.org.pl).

2.2 *Review of loadings*

All large sport-related structures are subject to a combination of loads which can be roughly divided into the self-weight loads (induced by the weight of the structure and its appendages), imposed loads (mainly due to spectator / pedestrian traffic load and maintenance) and the climatic loads. Climatic loads can be grouped into the various types of influences, i.e. temperature, rain, wind and snow. The latter one is irrelevant to South Africa but is of great relevance to Poland and Ukraine. *In fact, a series of tragic collapses due to snow load, of several large-span multipurpose roof structures across Europe (including Poland) led to the introduction of new design specifications based on the weight of accumulated* *snow/ice, and not the depth, being critical in assessing a roof's vulnerability.*

New Eurocode design specifications also place significant emphasis on loading considerations of the construction stages of large facilities. This is in terms of the different impact / contribution of various types of loading during the construction process and differences in structural robustness of complete versus partially erected structures during construction (e.g. stability of the elements, safety and integrity at all construction stages).

2.3 *Importance of wind loading*

For all light-weight large-span surfaces, like sport stadia, wind action constitutes the most critical structural loading. This is typically in terms of the overall stability due to wind uplift (often larger or comparable to self-weight) and also extreme loading over limited areas affecting the design of fixings of the covering membrane. For example, a rough estimate of uplift loading of a continuous roof structure, covering a grandstand accommodating 40 thousand spectators, is about 10 000 kN (i.e. 1 000t).

In contrast with the self-weight which can be determined relatively accurately, a huge problem in predicting the wind action is posed by the instantaneous application of the loading (due to the non-steady nature of flow), the dependence of the wind response of the structure on the specific flow regime which is generated, as a function of wind direction and also the possible dynamic / fatigue effects.

Finally, in the case of large span structures the most critical is the potential safety consequences of structural collapse due to wind loading, which could be catastrophic in terms of human losses.

The quantification of these risks is very difficult in view of the intermittent / accidental nature of wind loading and also due to the long-term climatic changes and trends which are difficult to research and quantify on the basis of short-term full-scale climatic records. For example, historically most the wind related damages in Poland (and most of Europe) were related to frontal wind events generated in winter-storms. In the past 10 to 15 years damage inflicted by intense thunderstorms has increased tremendously.

The other problem in quantifying the consequences of risks of wind induced failure is the seasonal characteristics of wind climate, which could be profound like in many areas of South Africa. From risk and structural reliability point of view the robustness of the structure should be considered in terms of a joint probability of occurrence of extreme wind event in combination with the extensive utilisation of the facility at the same instance of time (i.e. an occurrence of a specific large sport event attracting large number of spectators).

2.4 *Role of wind loading codification*

The overriding role of wind loading codification is to provide the design engineer with a set of statistically sound principles and parameters which will ensure the provision of safe and reliable structures under the critical wind loading.

In terms of the basic principles, the wind loading of structures L_{wd} can be encapsulated by the following function $L_{w,d} = f(v_d, R_w)$ where v_d is the characteristic design wind speed (reflecting the geographical locality, type of the surrounding environment and characteristics of the structure) and the response of the structure R_w (which reflects the ability of the structure to generate pressures and forces due to its geometrical form and aerodynamic 'porosity').

Like many other loads considered in the design, wind speed is a statistical quantity and its applicable loading level / implications should be considered in conjunction with societal and acceptable levels of risk of failure (which are typically built-in via the design mean return period and / or a set of importance factors.) These usually refer to the description of the magnitude of the approach wind speed affecting the specific design.

In view of the variety of possible building form configurations of large stadia, as well as the implications of potential failure, most design loading standards do not include information on the structural loading response of such structures. In most countries, strict design requirements exist which enforce the undertaking of relevant wind-tunnel studies of large / tall buildings, sport facilities or long-span bridges.

Following the stipulations included in old loading codes, the current version of the South African loading code SANS 10160-1989 includes a stipulation on grand stand roofs. This information refers to isolated structures and is not applicable to grandstands encircling the entire stadium, where the interference effects from the upwind sections of grandstands can be significant (Melbourne 1995).

3 RELEVANCE OF WIND-TUNNEL MODELLING

3.1 *Manifestation of specific situation*

Boundary-layer wind-tunnel technology enables the representation in model-scale of the specific full-scale situation of individual structures before construction takes place. This is most relevant in terms of several important characteristics of the surroundings, namely:

- approach flow conditions (terrain roughness,
- topographical influences, and
- the influence of prominent structures in the immediate vicinity.

Furthermore, wind-tunnel modelling is the only realistic way of truthful reproducing the actual geometry, aerodynamic relationships and flow regimes developing over structures.

3.2 *Optimisation of roof shape*

In view of the magnitude of wind forces, which can be generated over the roofs (Section 2.3), the determination of reliable values of the wind load is critical. Wind-tunnel technology enables the modelling of the specific form and shape of the roof, and importantly its spatial relationship with the grandstand, which determines the wind flow regime over the entire stadium. This is also determined by the continuity and slope of the roof structure and its relationship with other elements (e.g. side panels). In this respect, various possible geometries / solutions and sizes can be modelled and their loading implications can be quantified in the wind-tunnel (Goliger 2010).

3.3 *Architectural aspects of safety and functionality*

The main function of large sport stadia is to safely and functionally accommodate sport events. This is primarily considered in terms of the optimisation of the wind environment which will prevail over the pitch, affecting the fairness and spectacle of the game. However, other important aspects are related to the wind conditions and comfort of spectators at the grandstands, over the pedestrian traffic routes within the stadia and the general access areas envisaged for public utilisation (e.g. commercial or parking zones).

As large structures are known to generate adverse wind conditions, the above mentioned issues are relevant both in terms of safety and functionality aspects. These impacts can be quantified in the wind-tunnel and specific / optimal remedial measures to reduce these effects can be identified.

3.4 *Safety of construction stages*

The construction of all significant civil and building structures takes a substantial amount of time. During this time, the form and structural robustness of various components can markedly differ from those envisaged in the final structure. For example, the loading of a section of a completed roof (as presented in Figure 1) will drastically differ from that of the final roof. This will typically translate to ‘internal’ sections of the roof, designed for a relatively low magnitude loading, being subjected to extreme loading while remaining at the ‘edge’ during the construction process.

In recent years, there have been several building failures reported internationally and locally, which occurred during construction stages. Many (if not most) of them were triggered by different load distributions, which accompanied the construction stages and were not predicted at the design stage. Modern international design and loading manuals take this issue into account and place responsibility, on the related safety consideration during the construction process, on the structural designer.

The wind-tunnel technology offers a convenient way of investigating the loads relevant to various construction stages, by means of placing and testing sections of the model only.

3.5 *Influence / loadings of appendages*

Modern sport stadia are often equipped with large screens, information or advertisement boards attached to supporting structures or roofs. Such additional elements can substantially modify the wind flow and influence the loading of the supporting elements as well as the respective attachments. It is only possible to predict such influences either by using the physical scale-modeling or full-scale measurements on the completed structures.

The presence of such elements has direct safety implications due to risks of large scale elements (e.g. sections of the screens) becoming windborne debris. Wind-tunnel testing enables the modeling of the presence of such elements as well as measure the respective loading which is generated.

4 CONCLUDING REMARKS

This paper includes a review of various aspects of the structural and architectural design of large sport stadia. It also provides background regarding the importance of wind action and the relevance of wind-tunnel technology as a tool to address the design challenges.

5 ACKNOWLEDGMEENTS

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