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Computational wind engineering of large umbrella structures

Alexander Michalski [a,*], Bernhard Gawenat [a], Philippe Gelenne [b], Eberhard Haug [b]

[a] SL-Rasch GmbH, Stuttgart, Germany
[b] ESI France, France

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ABSTRACT

The sensitivity of membrane structures to transient wind loads becomes severe at wide spans and low pre-stress levels of the membrane. At stationary wind loads, the elastic behaviour of the flexible membrane leads to deformations with an associated change of the flow conditions and wind pressure distributions. This effect can be enhanced by time dependant fluid fluctuations such as atmospheric or building induced turbulences. Common methods in wind engineering practise like small scale wind tunnel experiments do not fully cover non-linear structural behaviour, contact interaction between membrane and structural elements and the interaction of the flow field with the structural response. Therefore numerical tools are used for the structural design of lightweight membranes. This paper presents results of the first industrial application of the fully coupled fluid structure interaction simulation for aerodynamically sensitive membrane structures situated in a built environment. The dynamic behaviour for gust induced wind loads has been investigated and reaction forces were determined. The application of the fully computational wind engineering method, in time domain, allowing as well for non-linear structural effects as for fluid structure interaction effects, makes the discovery of large dynamic amplification factors possible. The described procedure and results were reviewed and approved by Buro Happold, one of the world leading structural engineering offices.

1. Introduction

SL-Rasch, an internationally operating architectural and engineering office, located in Stuttgart, Germany, is specialized in the architectural and structural design of lightweight structures. One of the major tasks during the last years was the design of a large span convertible umbrella structures in collaboration with Liebherr, the world leading company of designing and manufacturing telescopic mobile cranes. The umbrellas are made of textile membranes and high strength steel (Fig. 1) and woven PTFE fabric with an edge length of 53 m and an eave height of 30 m. The convertible function of umbrellas mainly serves to protect pedestrians from direct sunlight, with the umbrellas fully open during the day, and to radiate heat stored during the day up to the night sky, when the umbrellas are fully closed overnight (Fig. 2). The convertibility has been accomplished by driving the telescopic umbrella arms and a central sliding ring so that the membrane is gathered around the mast. It completely disappears under covers made of fibreglass reinforced composite flaps which are separately driven individual elements. The covered area of 53 m umbrella is approximately 2500 m^2.

The sensitivity of the 53 m umbrella structure to transient wind loads becomes severe due to its wide span and low pre-stress levels of the membrane. Furthermore, the fact that external loads are collected by the membrane and are transferred by the arms to a single cantilevered mast amplifies the phenomenon. At stationary wind loads, the elastic behaviour of the flexible structure leads to deformations with an associated change of the flow conditions and wind pressure distributions. This effect can be enhanced by time dependant fluid fluctuations such as atmospheric or building induced turbulences.

Common methods in wind engineering practice, like small scale wind tunnel experiments, do not fully cover non-linear structural response, contact interaction between membrane and structural elements and the interaction of the flow field with the structural response. Therefore numerical tools, developed and validated during several scientific and applied engineering studies (Haug et al., 2009; Michalski et al., 2009, 2011) are used for the structural design of the 53 m umbrella.

The objective is to investigate the dynamic response of large convertible funnel shaped umbrellas made of high strength steel, under turbulent wind loads applying computational wind engineering tools. The task is to use a numerical software environment

* Corresponding author.
E-mail addresses: michalski@sl-rasch.de (A. Michalski), phg@esi-group.com (P. Gelenne), eberhard.haug@esi-group.com (E. Haug).

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Fig. 1. Prototype of a 53 m umbrella, SL-Rasch GmbH at the factory site of Liebherr.

to detect aero-dynamic instabilities and to assess dynamic structural response. Results are used for the structural design of the load bearing members and for the development of the folding kinematics. Further studies cover the behaviour of partially opened membrane structures in turbulent wind conditions. All simulations shown in this report are performed in time domain to allow for non-linear effects.

2. Computational wind engineering approach

2.1. Methodology

The complete simulation methodology, consisting of the numerical wind flow simulation and the fluid–structure coupling simulation, is presented in Fig. 3. Especially the application of well-established physical wind tunnel tests on small models is problematic due to the extremely small thickness of the membrane. Moreover, a problem occurs in small scale wind tunnel tests, when large deformations of thin membranes interact with the fluid flow, because similarity conditions of both, the flow and the structural vibrations, are difficult to match. Small thickness dimensions of the membrane and large structural deformation under wind loads can be accommodated readily in numerical simulations. The applied fluid structure interaction (FSI) simulation methodology (Michalski et al., 2010, 2011; Löhner et al., 1994, 1995) allows the realistic description of the non-linear structural behaviour at real-scale, which is especially important in the case of textile structures, and of the stochastic wind excitation, as both phenomena are modelled in time domain.

The unknown parameters of the flow (velocity and pressure) as well as of the structure (forces and deformations) are calculated including the fluid–structure coupling conditions. The partitioned FSI solution approach realized in the commercial PAM software environment of the company ESI Group, Paris, is applied (PAM-FLOW Manuals – Version, 2009; PAM-CRASH Manual – Version, 2010; PAM-LISA™ – Version, 2000). This fully partitioned approach guarantees a maximum flexibility in software and hence allows for each subtask the use of the best-suited and already tested solution schemes with their own best discretizations (Löhner et al., 1994,1995).

Structural wind load simulations employ Computational Fluid Dynamics (CFD) codes to simulate the wind and to evaluate the dynamic wind loads on structures. The wind loads can fluctuate due to turbulence inherent to the wind itself ("natural wind structure") and due to turbulence induced by close-by neighbour buildings and by the investigated building itself.

The standard software packages used are the Computational Fluid Dynamics (CFD) code PAM-Flow and the Computational Structural Dynamics (CSD) code PAM-Crash.

One major challenge of the numerical wind simulation on buildings is the correct reproduction of the natural wind conditions in the up-stream direction of the flow. In other words, the inflow conditions of the fluid flow domain must be defined according to the required conditions of the task. A specific wind module has been built and integrated into the ESI PAM-Flow software, which contains the generation of multi-correlated wind velocity time series and specific interpolation routines (Michalski et al., 2011; Mann, 1998). For detailed information about the numerical methods refer to Haug (1972), Haug et al. (2009), Löhner et al. (1998, 2004, 2006) and Löhner (2008).

The shown design procedure, dealing especially with non-linear dynamic problems, is not covered by the building code. As the presented numerical methodology is computationally expensive, up to now, only limited physical durations of 30 min could be simulated within an acceptable time frame during an industrial project. The special case of uncertainty due to a limited duration of the dynamic simulation, which arises in time domain analysis for the determination of extreme response under wind loading, is addressed by an expert study (Straub et al., 2012). A reliability-based approach to account for this uncertainty in a semi-probabilistic design format is proposed and applied within this project. A quantitative relation between the computational efforts made in design and the additional safety required is established (Straub et al., 2012).

The fluid–structure interaction simulation has been applied for the determination of the structural response of a 29 m umbrella under transient wind loads (Michalski et al., 2011). As results of