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Gust response envelope approach to the equivalent static wind load for large-span grandstand roofs

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ABSTRACT

Current equivalent static wind load (ESWL) format is expressed by either gust response factor (GRF) approach or the combination of mean, background and resonant components. Due to the complexity of fluctuating wind load characteristics and dynamic structural features of large-span roofs, the current ESWL formats are either too simplified or too complicated to be codified in wind load codes. In consideration of engineering convenience, this paper presents a gust response envelope (GRE) approach to express the ESWL model by the combination of mean and RMS wind pressures to envelope the wind-induced responses. The coefficient multiplied by the RMS wind pressure is defined as the GRE factor, which can be expressed by the product of the background and resonant factors. The background factor, based on gust loading envelope (GLE, Chen and Kareem, 2004), reflects the effect of asynchronous fluctuating wind loads on structures. The resonant factor denotes the dynamic effect of structures. The ESWL format is applied to the codification of wind loads on large-span cantilevered grandstand roofs. Parametric wind-induced response analyses were carried out, and the empirical formula of the GRE factor were provided for engineering reference.

1. Introduction

Current equivalent static wind load (ESWL) format is expressed by either gust response factor (GRF) (Davenport, 1967) approach or the combination of mean, background and resonant components (Chen and Kareem, 2001, 2004). The temporal and spatial characteristics of wind loads on large-span roofs are complicated due to body-induced turbulence. The large-span roof structures, characterized as flexible and light-weighted, are generally wind-sensitive. Furthermore, the vibration properties of large-span roof structures are also complicated. In particular, when the natural frequencies of many modes are close to each other, modal coupling phenomenon becomes important in the dynamic response analysis (Fu et al., 2008; Yang et al., 2013). Moreover, on the wind-induce responses of large-span roof structures, both the background and several resonant modal contributions are of similar importance (Holmes, 1996). Considering complicated characteristics of wind-induced responses of large-span roofs are, the GRF approach to express the ESWL seems to be too simplified, resulting in inadequate evaluation of wind loads (Yang et al., 2013; Katsumura et al., 2007; Rizzo and Sepe, 2015). On the other hand, the format combined by mean, background and resonant forces seems too complicated to be accepted and grasped by structural engineers. Therefore, a practical equivalent static wind load (ESWL) format for large-span roofs is hoped to be proposed.

Davenport (1967) suggested the gust response factor (GRF) approach for along-wind displacements of high-rise buildings. The concept was then developed for other response components (Kareem and Zhou, 2003). GRF is applied worldwide in building codes for high-rise buildings such as ASCE 2010 (USA), AS/NZ 2011 (Australia and New Zealand) (Australian/New Zealand Standard, 2011) and Eurocode 2010 (Europe) (European Committee for Standardization (CEN), 2010). Kasperski (1992), Kasperski and Niemann (1992) proposed the load-response-correlation (LRC) method to present a most probable load distribution for a specific background (quasi-static) response. In order to take the dynamic effect into account, Blaise and Denoël (2013) presented displacement-response-correlation (DRC) method, aiming at producing a set of ESWLs for each structural response based on the dynamic displacements. The ESWL theories mentioned above focus on a single

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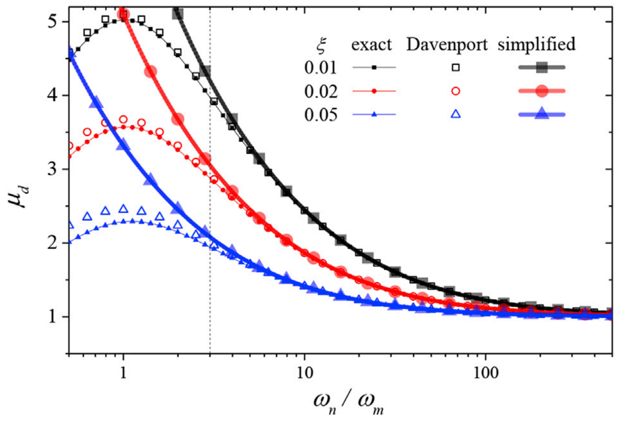


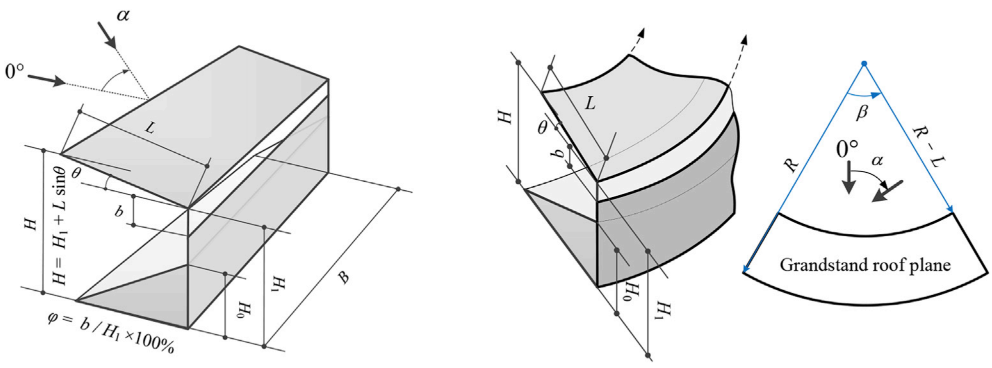
Fig. 1. Result of SDOF analyses.

equivalent object such as the displacement or base moment of a single degree-of-freedom (DOF) structure, which requires combination or selection of several potential unfavorable ESWL cases to provide more accurate design wind load. However, it may take much effort to combing the cases in engineering application, especially for complex projects.

An alternative definition for ESWL focuses on the envelope of structural responses for the convenience of application. Chen and Kareem (2004) proposed gust loading envelope (GLE) as to redefine the background (quasi-static) ESWL. This approach resulted in a simplified but physically meaningful load description as the RMS wind load multiplied by a background factor, which represents the effect of asynchronous wind load. The GLE approach with unity background factor turned out to converge to the LRC approach when the wind loads are fully correlated. The GLE approach was developed for both uncoupled and coupled wind-induced motion components on high-rise buildings and low-rise buildings. Katsumura et al. (2007) proposed a concept of universal ESWL distribution to reproduce simultaneously the absolute maximum responses in all structural members using combinations of proper orthogonal decomposition (POD) eigen-modes. Even though the universal ESWL based on POD modes provide a comprehensive envelope of peak wind-induced responses, the accuracy depends on the selection of POD modes, which is not easy to grasp, thus the practicability was undermined somehow. Li et al. (2009) divided the responses into groups, to improve the practicability of the method. However, the partition criterion is based on engineering experience. Zhou et al. (2011) solve this problem with least-square approach, which also relies on engineering judgement that can hardly be incorporated into wind load codes. Blaise and Denoël (2013) reconstructed the envelope of responses of DRC results as principal static wind load (PSWL) based on singular value decomposition (SVD). Rizzo and Sepe (2015) defined equivalent static pressure fields that can reproduce the envelope of dynamic displacements of the cables net for hyperbolic paraboloid roofs, using correction factors applied to envelope of experimental pressure coefficients.

On the spatial distribution format of ESWL, most current codes such as ASCE 2010 (ASCE, 2014), AS/NZ 2011 (Australian/New Zealand Standard, 2011) and Eurocode 2010 (European Committee for Standardization (CEN), 2010) choose the mean wind load multiplied by GRF or dynamic response factor especially for tall buildings (Dae and Kareem, 2013). The approaches employed was based on quasi-steady theory, moreover, the GRF approach was for single response target or mode, which cannot be applied into roof structures due to the significant body-induced turbulence and multiple modal vibration characteristics. In the Recommendations for Loads on Buildings published by the Architectural Institute of Japan (2015) (Architectural Institute of Japan (AIJ), 2015), roof wind load for structural frames are provided by the sum of the mean and fluctuating components of wind load. The fluctuating wind load is derived from the first modal force (Uematsu et al., 1996, 1997, 2008). Considering the multi-modal contributions for complicated structures, the application format is limited to simple structures. In some studies on bridges and high-rise buildings, the ESWL is composed of mean, background and resonant components (Chen and Kareem, 2004). The background component is provided by the GLE approach, while the resonant component is expressed as modal inertial force. The combination coefficients are determined by the weight of each response component. However, such a combination of the background and resonant components seem unrealistic for roof structures, because it is practically hard to perfectly separate the resonant component from the total response due to the background-resonance coupling. Moreover, the contribution and combination criteria of these components are to be determined based on a specific engineering situation, which demands complex calculations and intuitive understanding.

In the engineering practice of grandstand roofs, despite its wide engineering application, only Australian/New Zealand Standard (Australian/New Zealand Standard, 2011)provides a triangular ESWL distribution on rectangular plane roof in a wind normal to the leading edge of the roof for considering the dynamic effect (Melbourne, 1995). Killen and Letchford (2001) suggested a simplified trapezoidal ESWL distribution in place of the triangular one to get a better approximation for the quasi-static part of wind loading. For the aerodynamic wind loads on the grandstand roofs, which is sensitive to the roof geometry, Barnard (Banard, 1981) investigated the inter-relationships between roof pitch, wind azimuth and sub-roof blockage (ventilation rate) through wind tunnel tests, in which special attention is paid to the impacts of sub-roof blockage on flow patterns and wind load. Kawai (Kawai et al., 1999) investigated the wind-induced response of large cantilevered roofs using an aero-elastic model, positive aerodynamic damping force acting on the roof was found, which means, calculating the wind-induced response using the wind tunnel data on rigid model is safe in practice. Barnard



(a) rectangular plane

(b) arc-shaped plane

Fig. 2. Schematic diagram of model geometry.