Definition of storm duration and duration effects on structural elastoplastic response

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SUMMARY:
To evaluate structural elastoplastic wind effects and performance under rare strong storms, this study proposes definition of storm intensity and duration according to wind load characteristics by referring to the seismic Arias intensity. The storm intensity can indicate the possible structural elastoplastic response and damage. A storm duration is defined as the minimum acting time when the energy accumulation in the storm reaches the same proportion of the proposed storm intensity. The rationality of definition of the storm intensity and duration is verified, and the storm duration effects on structural elastoplastic responses are investigated. The wind-induced responses of single-degree-of-freedom (SDOF) structures are numerically analyzed using the measured wind data. The results show that the storm intensity is valid to measure the relative destructiveness of a storm on all buildings of a region. The structural peak elastoplastic displacement and damage accumulation tend to dramatically increase with the increase of storm duration.

Keywords: elastoplasticity, storm intensity, storm duration

1. INTRODUCTION

The wind design of buildings is moving towards performance-based methodology permitting the structural plastic deformations under rare strong winds(Chuang and Spence, 2017). Structural elastoplastic responses may increase with the increase of the duration of strong winds(Feng and Chen, 2018). While the current research on the effects of loads duration on structures is mainly concentrated in the earthquake engineering community (Raghunandan and Liel, 2013). There are few studies on duration in wind engineering community, hence there is no recognized wind duration definition and no clear knowledge of the effects of wind duration on elastoplastic structural wind responses at present. In this study, definitions of storm intensity and duration are proposed for the performance evaluation of structures under rare strong winds. Furthermore, storm duration effects on the elastoplastic of SDOF structure are investigated.

2. DEFINITION OF STORM INTENSITY AND DURATION

The most commonly used indicator of storm intensity is the 10-minute mean wind speed ($U_{\max}$) for structural elastic response, but structural elastoplastic responses are closely related to the time histories and duration of storms besides $U_{\max}$ under rare strong winds. Therefore, it is necessary to define a storm intensity and storm duration to evaluate the structural elastoplastic response.

2.1. Definition of Storm Intensity

As the seismic Arias intensity(Arias, 1970) was proved to reflect the structural damage accumulation, this study proposes the storm-intensity definition by drawing on the Arias intensity. The difference between wind loads and earthquake loads are distinguished. The magnitude of the wind loads is mainly related to building shapes rather than the building mass. As a result, the Arias intensity cannot be directly applied to define storm intensity. The storm-intensity definition is derived by referring to the Arias intensity. Assuming that the wind load acting on buildings conforms to the quasi-steady assumption, the wind-load time history is expressed as Eq.(1).

$$F_v(t) = \frac{1}{2}\rho A C_P V(t)^2 = \frac{1}{2}\rho A C_P [U(t) + v(t)]^2 \tag{1}$$

Where A is the windward area, C_P is the wind pressure coefficient, $V(t)$ is the total wind speed, $U(t)$ is the mean wind speed, and $v(t)$ is the fluctuating wind speed. The time history of mean wind speed of a storm is commonly obtained from the measured wind data. The time history of fluctuating wind speed can be generated by inverse FFT using the wind velocity spectrum.

The structural initial velocity and displacement before the storm are assumed to be 0. The structure after the storm will eventually stop vibrating with the time increase due to the damping energy dissipation, so there is no variation of kinetic energy and elastic strain energy after the structure suffers a whole storm. According to the conservation of energy, the work of the storm on the structure is completely dissipated by the structural damping as expressed in Eq. (2).

$$\int_0^T F_v(t)\dot{x}(t)dt = 2m\omega\xi \int_0^\infty \dot{x}(t)^2 dt \tag{2}$$

Where T is the actual duration of a storm, the left side of the equation is the work of the storm on the structure, and the other side is the energy dissipated by damping.

Although the elastic dissipated energy is not an intensity indicator directly related to the structural damages, past studies pointed out that the elastic dissipated energy of SDOF structures correlates well with the elastoplastic dissipated energy, and can be used to evaluate the severity of structural damages. Hence it may be reasonable to use the elastic dissipated energy to predict the relative severity of structural damages induced by a storm. To make the storm-intensity definition and the subsequent storm-duration definition widely applicable, the storm intensity I_C is defined as the sum of dissipated energy of all structures in a region for measuring relative destructiveness of a storm on all buildings of the region. Assuming that the number of structures whose frequencies lie in the interval (ω, ω+dω) is proportional to dω, the storm intensity is expressed as Eq. (3).

$$I_C = \int_0^\infty E(\omega)d\omega = \int_0^\infty d\omega \int_0^T F_v(t)\dot{x}(t)dt \tag{3}$$

The analytical solution of storm intensity is obtained after a series of derivations. As the structural dissipated energy only change a little when ξ changes between 0 and 0.1, ξ is eliminated by substituting ξ=0 into Eq. (4). And the final equation of storm intensity I_C is shown in Eq. (5).

$$I_C(\xi) = \frac{\arccos\xi}{m\sqrt{1-\xi^2}} \int_0^T F_v(t)^2 dt \tag{4}$$

$$I_C = \frac{\pi}{2m} \int_0^T F_v(t)^2 dt \tag{5}$$

As shown in Eq. (5), the expression of the proposed storm intensity is similar to that of the Arias intensity, but the expressions of the load time history are distinctly different.

2.2. Definition of Storm Duration

The actual storm usually lasts for a long time up to tens of hours, and a significant proportion of storm does not produce structural damages. Hence, how to effectively extract the strong winds or truncate the weak winds from a storm plays a significant role in reducing computation time.

There are dozens of duration definitions in the earthquake engineering community, among which the significant duration based on the Arias intensity is defined as the interval between time instants at which the Arias intensity reaches two different relative values respectively. Detailed studies of the significant duration show that it is very effective to extract the strong motion part from an earthquake by using relative proportion of the Arias intensity of (5%,95%) (Trifunac and Brady, 1975)or (5%,75%)(Somerville and Yoshimura, 1990), since the strong motion commonly only occur in the middle of the earthquake. However, the strong winds may occur in any time of a storm, and it means that the storm duration cannot be calculated by specifying two fix proportions similar to the significant duration. According to Eq. (4), storm intensity is essentially an energy, and the shorter the time when the energy accumulation in the continuous time period reaches the relative proportion αI_C (where α is the relative value coefficient) of storm intensity is, the more severe potential destructiveness of this part of wind storm will be. Hence, the storm duration is defined as the minimum acting time when the energy accumulation in the storm reaches the same proportion of storm intensity as shown in Fig 1. This study assigns α the value of 70% by referring to the energy threshold of 90% and 70% commonly used in significant duration.

3 NUMERICAL ANALYSIS

In this part, the SDOF structure using the ideal elastoplastic restoring force model is selected to verify the rationality of the definition of storm intensity in Section 2.1, and to study the effects of storm duration on the structural elastoplastic wind response. The wind speed data is obtained from the Amarillo Airport Weather Station. The independent storm method proposed by Cook (Cook, 1982) is used to divide the data into 1761 independent storms as the load databases for analysis.

3.1 Verification of The Rationality of Storm-intensity Definition

The total hysteretic energy dissipation I_{EP} of all structures under 20 independent storms is calculated respectively by Eq. (6), where $E_P(\omega)$ is the hysteretic energy dissipation of SDOF structure whose natural frequency is ω under a storm. The yield load f_y is the corresponding yield load when the structural ductility factor μ is equal to 2 under the storm. The relationship of I_C to I_{EP} is shown in Fig. 2. The equation of linear fitting curve is $I_{EP} = 1.26I_C + 5100.16$, and the r^2 is 0.93. Above results show that the storm intensity corresponds well with the structural hysteretic energy dissipation under storms, illustrating that the storm intensity is valid to predict the elastoplastic structural wind responses. It should be noted that the slope and intercept of the fitting curve will change with the variation of structural parameters and specified ductility factor.

$$I_{EP} = \int_0^\infty E_P(\omega) d\omega \tag{6}$$

3.2 Storm-duration Effects on Structural Elastoplastic Wind Responses

20 independent storms, whose U_{max} is in the range of 18m/s to 20m/s, are selected in the databases. And then U_{max} of these storms is unified to 19m/s through normalization. The f_y is the wind load when the wind speed is 19m/s/1.1. The relationship between storm duration and structural peak displacement, hysteretic energy dissipation and residual deformation is shown in Fig. 3 through structural dynamic time history analysis. Fig. 3 presents that the structural residual deformation is equal to the ratio of the hysteretic energy dissipation to f_y, since the mean wind keeps the structure in a one-direction yield state. Therefore, the structural peak displacement and damages tend to dramatically increase with the increase of storm duration.

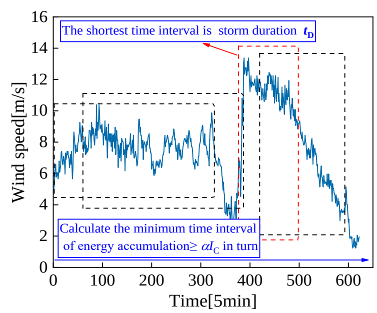

Fig 1 Storm duration

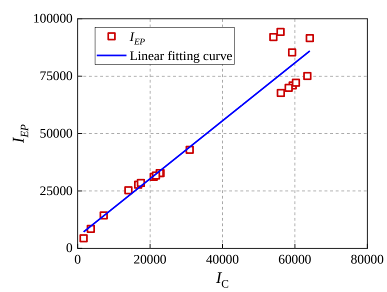

Fig. 2 I_C-I_{EP} relationship

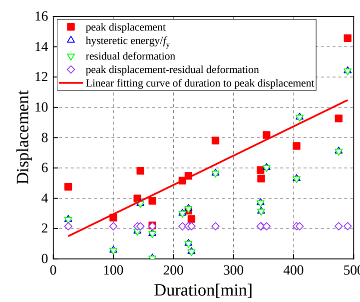

Fig. 3 Effects of storm duration

4. CONCLUSIONS

This study proposes definition of storm intensity and duration for elastoplastic performance evaluation. The storm intensity corresponds well with the structural hysteretic energy dissipation under storms. The elastoplastic displacement tends to increase with the increase of storm duration.

ACKNOWLEDGEMENTS

The work was partially supported by the National Natural Science Foundation of China (Grant No. 52078088).

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