

Collapse reliability of high-rise reinforced concrete systems subject to fully non-staight/-stationary hurricane representations

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ABSTRACT: Performance-based wind engineering is becoming rapidly recognized as a significant shift in wind engineering that places focus on inelastic performance evaluation over a full range of wind intensities, therefore enabling the design of engineered buildings with enhanced resiliency and optimal material utilization. Notwithstanding, there is still a lack of systematic simulation-based frameworks enabling modeling of the inelastic/collapse performance under non-stationary/-straight hurricanes of long duration. A computational framework that integrates a high-fidelity structural modeling environment with a stratified sampling-based scheme for uncertainty propagation is proposed in the work for efficiently investigating the inelastic/collapse behavior of structural systems under hurricanes. However, this framework soon becomes computationally intractable when estimating the inelastic response of high-rise buildings subject to full hurricanes of long duration. A common solution is to use nominal hurricanes (e.g., stationary and straight wind events of one-hour duration), but the accuracy remains unknown. To address this limitation, a truncated hurricane model that retains the critical non-stationary/-straight hurricane history is introduced in this work for modeling the accumulation of damage while fully capturing the time-varying nature of hurricane tracks. Through the illustration on a 45-story reinforced concrete archetype building, the proposed framework has been demonstrated to be capable of efficiently estimating probabilities of failure associated with rare events (e.g., collapse) under nominal hurricanes. Additionally, investigations into the collapse mechanisms associated with both the nominal and truncated non-stationary/-straight hurricane representations are compared, demonstrating the need to consider time-varying hurricane representations.

With the aim of ensuring enhanced resiliency and economy, the past decade has seen performance-based wind engineering (PBWE) widely accepted as an alternative to current elastic wind design procedures (Judd and Charney, 2015; Ciampoli et al., 2011; Chuang and Spence, 2019; ASCE, 2019; Chuang and Spence, 2020; Cui and Caracoglia, 2020; Ouyang and Spence, 2020, 2021; Huang and Chen, 2022; Chuang and Spence, 2022; Arunachalam and Spence, 2022). The desire to reap the

maximum benefits of PBWE has led to a number of research efforts that place focus on proposing efficient frameworks for assessing the inelastic/collapse behavior, as well as reliabilities, of engineered building systems subject to a full range of wind intensities and general uncertainties (Chuang and Spence, 2022; Arunachalam and Spence, 2022). Nevertheless, due to the computational effort, PBWE frameworks developed to date have rarely focused on assessing the performance

of structural systems subject to long-duration non-stationary/-straight wind excitation through nonlinear dynamic analysis using high-fidelity finite element models. Notwithstanding the wide application of nominal straight and stationary hurricanes in nonlinear wind analysis, the correspondence to the nonlinear response behavior of the system under actual non-stationary/-straight hurricanes remains unknown. In response to the increasing functional and residential demand for high-rise buildings (especially reinforced concrete (RC) buildings) together with the frequent occurrence of hurricanes, the need for explicitly assessing the inelastic performance of high-rise structural systems subject to non-stationary/-straight hurricane hazards is generally recognized.

To fill this gap, challenges are mainly related to the following aspects: (1) efficient hurricane models capable of capturing the full non-stationary/-straight nature of hurricanes; and (2) stochastic simulation schemes that allow efficient estimation of the small failure probabilities associated with limit states such as collapse. To tackle this, Ouyang and Spence (2021) proposed a PBWE framework based on a full description of the hurricane hazard. However, this framework will become computationally prohibitive if implemented in the collapse reliability analysis of high-rise RC buildings due to the long duration of full hurricanes as well as the complexity of the finite element models adopted for estimating extreme responses. This work develops a PBWE framework that integrates a high-fidelity structural modeling environment with a stochastic hurricane model for inelastic/collapse performance assessment of high-rise RC buildings subject to hurricanes. A stochastic stratified sampling simulation scheme embedded with a sector-by-sector approach is adopted to estimate the reliability related to rare events under nominal hurricanes. To account for the non-stationary/-straight nature of real hurricanes while ensuring computational feasibility, a truncated hurricane model is proposed that identifies the critical window of the non-stationary/-straight hurricane loads that result in significant inelastic responses. Through the illustration on an archetype 45-story RC building,

the efficiency of the proposed framework for reliability analysis based on dynamic nonlinear wind response analysis is demonstrated. Additionally, a comparative study is carried out to investigate the inelastic performance and collapse mechanisms associated with both a nominal and truncated non-stationary/-straight hurricane representation. The importance of investigating inelastic wind response and collapse under non-stationary/-straight hurricanes is emphasized.

1. PROPOSED FRAMEWORK

The proposed framework is based on characterizing the inelastic wind performance of the structural system through estimating the failure probability, P_{f_g} , associated with a limit state function of interest g , e.g., collapse, through solving the following probabilistic integral:

$$P_{f_g} = P(g(\mathbf{Y}) \leq 0) = \int_{\alpha} \int_{\bar{v}_H} f_{\mathbf{Y}|\alpha, \bar{v}_H}(\mathbf{y}|\alpha, \bar{v}_H) d\mathbf{y} |dG(\alpha|\bar{v}_H)| |dG(\bar{v}_H)| \quad (1)$$

where $\mathbf{Y}$ is a vector collecting the basic random variables associated with general uncertainties (in the following, uppercase notation will represent the random variable while lowercase notation will indicate a realization); $f_{\mathbf{Y}|\alpha, \bar{v}_H}$ is the joint probability density function (PDF) of $\mathbf{Y}$ conditional on the maximum mean hourly wind speed $\bar{v}_H$ and associated direction α ; $G(\alpha|\bar{v}_H)$ is the complementary cumulative distribution function (CCDF) of α conditional on $\bar{v}_H$; and $G(\bar{v}_H)$ is the CCDF of $\bar{v}_H$.

Core to solving Eq. (1) include aerodynamic models that capture the full nature of the non-stationary/-straight hurricanes as well as efficient frameworks that enable the propagation of uncertainty and subsequent estimation of small probabilities of failure. In contrast to a classic setting that adopts a nominal hurricane representation, Eq. (1) cannot be directly applied to cases involving non-stationary/-straight representations due to: (1) the time-varying mean hourly wind speed $\bar{v}_H$ and associated direction α , which cannot be treated as a basic random variable; and (2) the computational effort associated with estimating Eq. (1) for full hurricane events that have a duration in the order of several hours.

2. TRUNCATED HURRICANE MODEL

The proposed truncated hurricane model is based on the full hurricane model suggested in Ouyang and Spence (2021). The intensity of a site-specific non-stationary (time-varying average wind speed $\bar{v}_H(t)$) and non-straight (time-varying wind direction $\alpha_H(t)$) full hurricane is measured through the maximum mean hourly wind speed $\bar{v}_{max}$ to occur at reference height H (e.g., the height of the building of interest) during the passage of the hurricane. Subsequently, $\bar{\alpha}_{max}$ is extracted from $\alpha_H(t)$ at the time instant when $\bar{v}_{max}$ occurs. The choice of $\bar{v}_{max}$ as an intensity measure allows direct comparison between performance assessments carried out using a nominal and full hurricane representation considering a consistent wind intensity setting.

To reduce the computational effort as well as capture the progression of inelasticity, the hurricane representation corresponding to wind speeds less than a truncated wind speed $\bar{v}_{tr}$ is cut from the full hurricane representation, while the remaining representation collects the critical hurricane history that leads to significant inelastic behaviors. In this work, $\bar{v}_{tr}$ is suggested as the wind intensity that results in significant residual deformation (e.g., residual roof drift ratio exceeding 1/1000) and can be determined from a preliminary study of the structure of interest. To account for the path-dependent nature of inelastic analysis, an appropriate ramp-up and ramp-down at the beginning and end of the truncated hurricane representations should be considered.

3. SIMULATION STRATEGY

To efficiently estimate the small probabilities related to rare events (e.g., collapse) with limited computational effort, a stochastic simulation scheme that integrates the sector-by-sector approach with the stratified sampling scheme outlined in Arunachalam and Spence (2023) is adopted. By dividing the wind directions into N_s sectors, the critical sector that produces the most extreme wind response can be quickly identified by preliminary elastic dynamic response analysis. Subsequently, the hurricane hazard curve, defined as the probability of exceeding the maximum mean hourly wind speed during a hurricane irrespective of wind

direction, is partitioned into N_w mutually exclusive and collectively exhaustive subevents, called strata. The failure probabilities within each stratum, and with respect to all limit states of interest related to the inelastic wind performance, can then be evaluated using direct Monte Carlo methods as they no longer represent rare events. In this work, the proposed stochastic simulation is adopted for estimating the probabilities of failure considering a traditional nominal hurricane representation. Notwithstanding the significant gains in computational power of the last few decades, estimating the structural reliability subject to the full hurricane (which usually has a duration of over 10 hours) is still extremely computationally intensive. Therefore, in this work, to study the effects of non-stationary/-straight hurricanes, the critical samples of the simulation carried out considering a nominal hurricane representation are probabilistically reexamined considering non-stationary/-straight hurricane samples that are consistent with the nominal samples.

4. CASE STUDY

4.1. Building System

To illustrate the proposed framework as well as compare the inelastic performance assessments carried out using the nominal hurricane model as opposed to the truncated non-stationary/-straight hurricane model, a 45-story archetype RC building of height 180 m and hypothetical location New York City is considered. This building consists of four RC fin shear walls embedded with link beams, as illustrated in Fig. 1. Classified as a Risk Category II structure, the target probability of failure that results in widespread progression of damage is 3.5×10^{-6} (the associated reliability index β is 4.0) over a 50-year lifespan (ASCE 7-22, 2022). A high-fidelity fiber-based finite-element model is developed in *OpenSees* to investigate the inelastic behavior of the system. In particular, large deformation is captured through a corotational formulation, shear walls are modeled through fiber-based shell elements, and the nonlinear behavior of both the concrete and steel is captured through hysteretic material models that include the possibility of failure due to low-cycle fatigue in the steel.

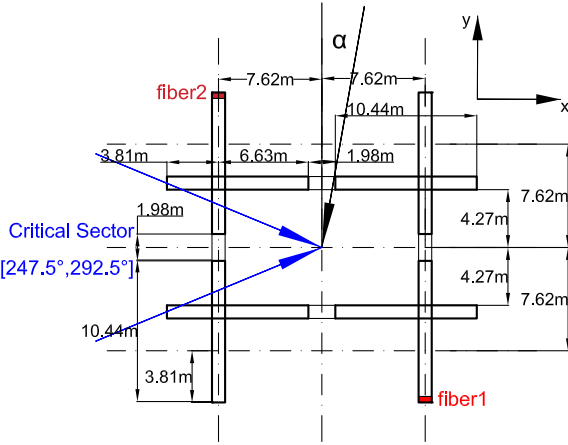


Figure 1: Building layout and critical wind sector.

4.2. Hurricane Hazard

To account for wind directionality when adopting the straight and stationary nominal hurricane representation, the wind directions are equally divided into 8 sectors. By implementing the sector-by-sector approach, the critical sector that produces the maximum elastic resultant base moment can be identified as $\alpha \in [247.5^\circ, 292.5^\circ]$, as illustrated in Fig. 1. In the critical sector, the sectorial wind speeds are assumed to follow a scaled version (scaling factors estimated from a local climatological study) of the non-directional wind speed distribution, which is fitted from the site-specific largest mean annual hourly wind speeds provided by ASCE 7-22 (2022). Within the critical sector, wind direction is considered to vary uniformly. Given a wind speed and direction in the critical sector, the nominal hurricane is generated from a data-driven proper orthogonal decomposition model calibrated to building specific wind tunnel test data on a 1:400 scale building model provided by Cermak Peterka Petersen (CPP) (Suksuwan and Spence, 2018). Subsequently, the truncated non-stationary/straight hurricane model was implemented to simulate samples with a maximum wind speed, and associated direction of occurrence, which was the same as the nominal hurricane samples causing collapse. In defining the truncation criteria, a truncation wind speed, v_{tr} , of 70 m/s was considered (i.e., the wind speed resulting in a residual roof drift ratio greater than 1/1000). The identification of v_{tr} was based on the performance assessment carried

out using the nominal hurricane representation. To ensure reasonable initial and final conditions, a linear ramp up over the first 30 s was considered, as was a linear ramp down over the last 30 s to which a 45 s zero loading was added to ensure the structure comes to a rest, therefore, allowing the direct estimation of the residual deformation in the system.

4.3. Results

4.3.1. Reliability assessment

To estimate the nominal reliability of the structure, 541 optimally chosen nominal hurricane samples were generated using the stratified sampling scheme. Each sample was associated with a realization of the random vector collecting the model uncertainties of the problem (e.g., random material properties, mass, and gravity loads). The resulting probability of failure with respect to the system collapse was estimated as 6.2×10^{-7} with a coefficient of variance (COV) of 20% over a 50-year lifespan. This value satisfies the reliability target reported in ASCE 7-22 (2022). These results illustrate how the proposed computational framework is capable of estimating small probabilities of failure with reasonable COVs using extremely limited sample sets.

To develop a general understanding of the underlying approximations associated with the use of a nominal hurricane representation, a comparative study was carried out to investigate the inelastic performance of the 20 nominal hurricane samples causing collapse. To this end, 20 truncated non-stationary/straight hurricane samples were generated that had the same wind intensities as the nominal hurricanes causing collapses. Each truncated non-stationary/straight hurricane sample was associated with the same vector of model uncertainties as the nominal hurricane samples. It is noteworthy that all 20 truncated non-stationary/straight samples also caused the collapse of the system. Fig. 2 and Fig. 3 report the histograms of the maximum compressive strain, ϵ_c , and maximum tensile strain, ϵ_t , of the critical fibers at the ground floor, as highlighted in Fig. 1. Since the truncated non-stationary/straight hurricane samples are selected based on producing the same maximum wind speed and associated direction, α_{max} , as the nomi-

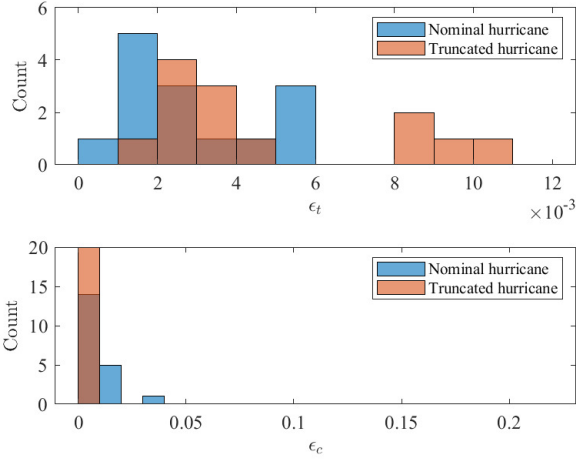


Figure 2: Histogram of the maximum strain in fiber 1.

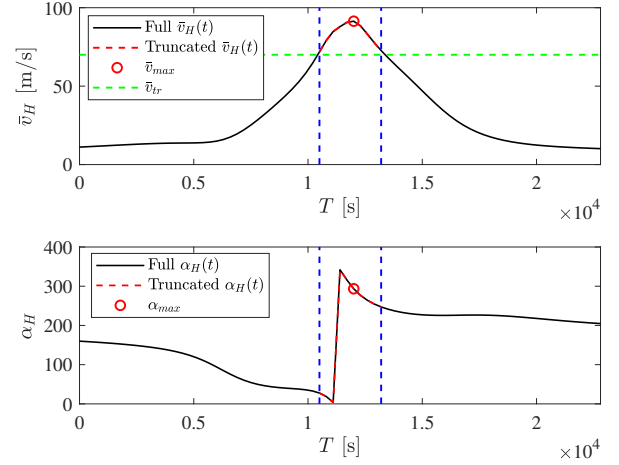


Figure 4: Truncated portion of $\bar{v}_H(t)$ and $\bar{\alpha}_H(t)$ with $\bar{v}_{max} = 91$ m/s and $\alpha_{max} = 290^\circ$ highlighted.

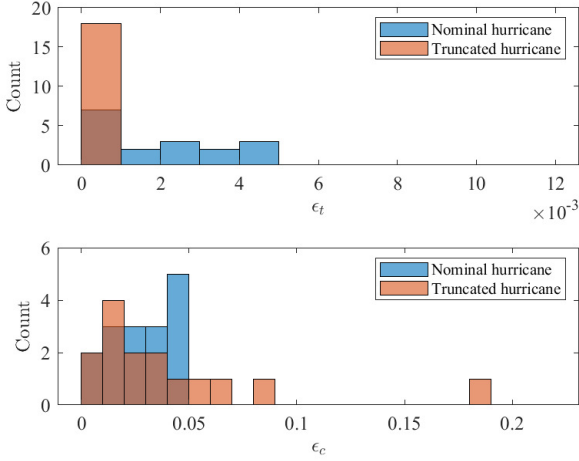


Figure 3: Histogram of the maximum strain in fiber 2.

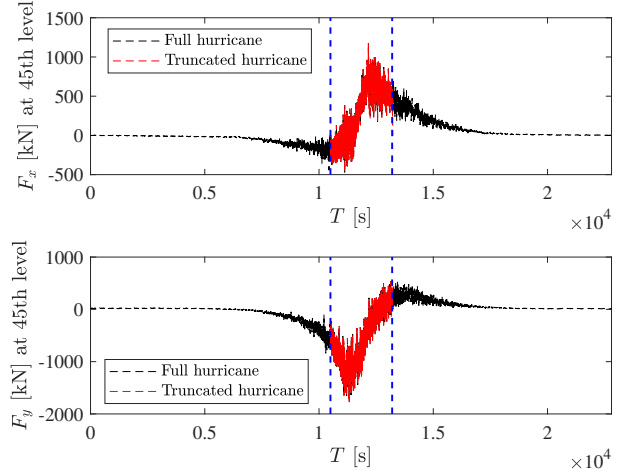


Figure 5: Truncated hurricane representation for $\bar{v}_{max} = 91$ m/s, $\alpha_{max} = 290^\circ$.

nal hurricane samples causing collapse, the wind directions, α_{max} , belong to the critical wind sector. As such, both fiber 1 and fiber 2 have comparable maximum compression and tension for both the nominal and truncated non-stationary/-straight hurricane samples. However, it can be observed that the truncated non-stationary/-straight hurricanes increase the maximum tensile strain for fiber 1 while simultaneously increasing the compressive strain for fiber 2. Therefore, the utilization of a nominal hurricane representation, as an alternative to the non-stationary/-straight hurricane, can lead to underestimates of both the compression and tension in critical fibers.

4.3.2. Collapse mechanism comparison

To enable the collapse mechanism comparison between the truncated non-stationary/-straight hurricane representation and the nominal hurricane representation, a single hurricane event is analyzed in detail in this section. The maximum wind speed, $\bar{v}_{max}$, of the sample was 91 m/s while the corresponding wind direction, $\bar{\alpha}_{max}$, was 290° . Fig. 4 illustrates the definition of the proposed non-stationary/-straight hurricane representation based on the full wind speed and direction history of the sample. It is noteworthy that the truncated non-stationary/-straight hurricane representation signif-

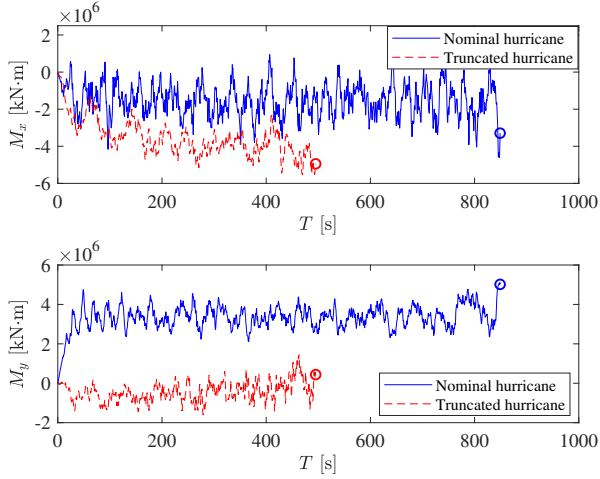


Figure 6: Response base moment comparison for $\bar{v}_{max} = 91$ m/s and $\alpha_{max} = 290^\circ$.

icantly reduces the duration of the full hurricane from 12.7 hours to a critical window of 1.5 hours, which enables high-fidelity computational modeling. Fig. 5 shows a comparison between the truncated and full hurricane stochastic wind loads at the top floor with respect to the along-wind (F_x) and across-wind (F_y) directions.

To examine the difference between the response of the structure to the truncated non-stationary/straight hurricane representation and the nominal hurricane representation, the response base moments time histories up until collapse in both the along-wind and across-wind directions (e.g., M_y and M_x) are shown in Fig. 6. It can be seen that the truncated non-stationary/straight hurricane representation produces a more extreme response base moment time history in the across-wind direction (M_x), which is the predominant wind direction of the truncated representation. With respect to the nominal hurricane, significantly different base moments are generated in the along-wind direction (M_y). This observation provides insight into why the truncated non-stationary/straight hurricane leads to a dominant flexure-based collapse in the across-wind direction while the collapse resulting from the nominal hurricane presents a diagonal flexure, as can be seen from the roof displacement (d_i) time history comparison of Fig. 7. Fig. 8 compares the peak inter-story drift ratios at the collapse

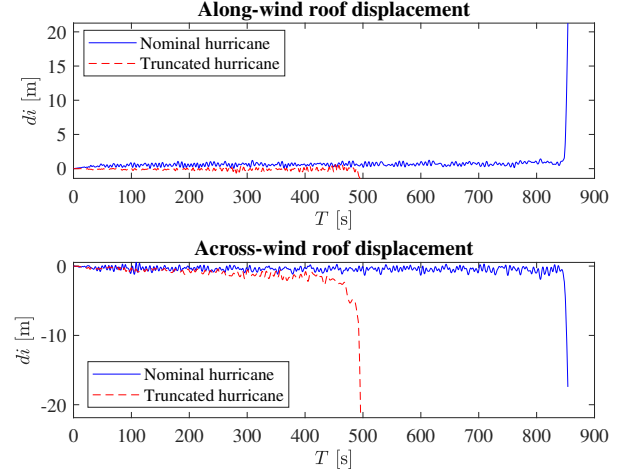


Figure 7: Roof displacement comparison for $\bar{v}_{max} = 91$ m/s and $\alpha_{max} = 290^\circ$.

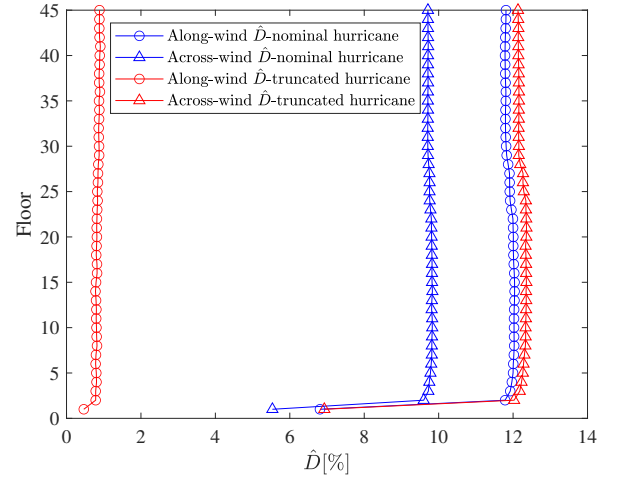


Figure 8: Peak inter-story drift ratio, $\hat{D}$, comparison for $\bar{v}_{max} = 91$ m/s and $\alpha_{max} = 290^\circ$ and collapse.

instant which provides further evidence of the difference in the collapse mechanisms. Despite the different collapse mechanisms, it is interesting to observe that at collapse the building suffers from similar peak drifts in the across-wind direction with severe damage at the base of the structure for both the nominal and truncated non-stationary/straight hurricane representations.

5. CONCLUSIONS

In this paper, a computational framework that integrates a high-fidelity structural modeling environment with a stratified sampling-based simula-

tion scheme is proposed to efficiently estimate the structural reliability of reinforced concrete structures to hurricanes. Through illustration on a 45-story archetype reinforced concrete structure, it is demonstrated that the proposed framework is capable of estimating the small failure probabilities related to rare events (e.g., collapse) with extreme efficiency. To account for the time-varying nature of real hurricanes, a truncated non-stationary/-straight hurricane model is proposed. It is noteworthy that the classic stationary and straight nominal hurricane representation can lead to an underestimation of the peak compressive and tensile strains in the critical fibers of the system. Additionally, a comparative study illustrated how the application of a non-stationary/-straight hurricane representation can lead to significantly different collapse mechanisms despite similar localized damage. This illustrates the importance of carrying out performance assessments using more realistic non-stationary/-straight hurricane representations if the true collapse behavior is to be captured.

6. ACKNOWLEDGEMENTS

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