

Extending Analytical Fragility Analysis to Nonlinear Structural Systems: ANFA Method

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Anahtar Kelimeler

Kırılabilirlik analizi
Performansa dayalı rüzgar
mühendisliği
Stokastik rüzgar yükü
Doğrusal olmayan dinamik
sistemler
Monte Carlo simülasyonu
Yapısal güvenilirlik

Graphical/Tabular Abstract (Grafik Özet)

The proposed ANFA method efficiently derives fragility curves of nonlinear structural systems under stochastic wind loading using frequency-domain response estimation and a capacity-consistent threshold displacement definition. / Önerilen ANFA yöntemi, stokastik rüzgar yükleri altındaki doğrusal olmayan yapısal sistemlerin kırılabilirlik eğrilerini frekans alanı tepki tahmini ve kapasite uyumlu eşik yer değiştirme tanımıyla hesaplama açısından verimli şekilde elde etmektedir.

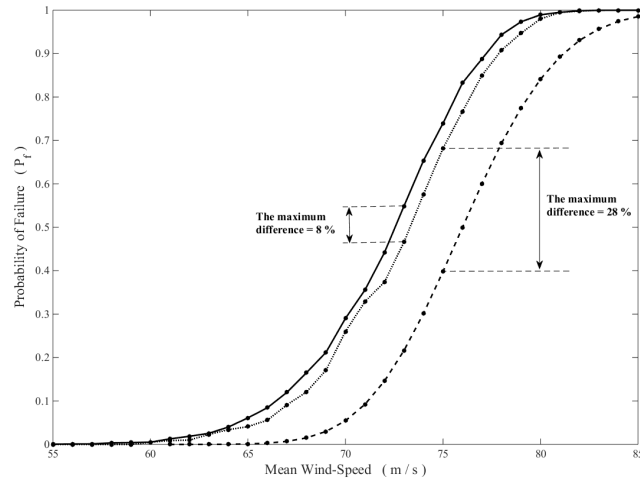


Figure 4. The fragility curves of the non-linear dynamic 3-DOF system using ANFA (solid line), MCM (dotted line), and LEM (dashed line) (ANFA (sürekli çizgi), MCM (noktalı çizgi) ve LEM (kesik çizgi) kullanılarak elde edilen doğrusal olmayan dinamik 3 serbestlik dereceli sistemin kırılabilirlik eğrileri)

Highlights (Önemli noktalar)

- The proposed ANFA framework extends the ALFA approach to nonlinear structural systems. / Önerilen ANFA çerçevesi, ALFA yaklaşımını doğrusal olmayan yapısal sistemlere genişletmektedir.
- Nonlinear capacity is represented by the threshold displacement corresponding to the plastic moment capacity. / Doğrusal olmayan kapasite, plastik moment kapasitesine karşılık gelen eşik yer değiştirme ile temsil edilmektedir.
- ANFA produced fragility curves close to those obtained from Monte Carlo simulation. / ANFA, Monte Carlo simülasyonuna yakın kırılabilirlik eğrileri üretmiştir.

Aim (Amaç): To develop ANFA for efficient fragility assessment of nonlinear wind-excited structural systems. / Doğrusal olmayan rüzgar etkisindeki yapısal sistemlerin verimli kırılabilirlik değerlendirmesi için ANFA yöntemini geliştirmek.

Originality (Özgünlük): Nonlinearity is incorporated through a capacity-consistent threshold displacement instead of repeated nonlinear time-history analyses. / Doğrusal olmayan davranış, tekrarlı doğrusal olmayan zaman tanım alanı analizleri yerine kapasite uyumlu eşik yer değiştirme ile dikkate alınmıştır.

Results (Bulgular): ANFA closely matched MCM with a maximum difference of about 8%, while LEM differed by about 28%. / ANFA, MCM ile yaklaşık %8 maksimum farkla uyum sağlamış; LEM'de fark yaklaşık %28'e ulaşmıştır. (EN).

Conclusion (Sonuç): ANFA offers a practical and computationally efficient alternative for preliminary nonlinear wind fragility assessment. / ANFA, ön doğrusal olmayan rüzgar kırılabilirlik değerlendirmesi için pratik ve hesaplama açısından verimli bir alternatif sunmaktadır.



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Abstract

Performance-based wind engineering requires computationally efficient fragility assessment methods for structural systems subjected to stochastic wind loading. Although Monte Carlo simulation is widely used as a reference approach for constructing fragility curves, its application to nonlinear dynamic systems may require numerous nonlinear time-history analyses and therefore lead to high computational cost. This study proposes an Analytical Nonlinear Fragility Analysis (ANFA) framework to extend the frequency-domain response-estimation philosophy of Analytical Linear Fragility Analysis (ALFA) to nonlinear structural systems. The proposed method preserves the efficiency of harmonic decomposition and frequency-response-based response estimation, while nonlinear structural behavior is incorporated through a capacity-consistent threshold displacement corresponding to the plastic moment capacity. The applicability of the framework is demonstrated using a nonlinear three-degree-of-freedom mass-column system subjected to stochastic wind excitation. A bilinear moment-curvature relationship is used to represent material nonlinearity, and fragility curves are developed for mean wind speeds ranging from 55 to 85 m/s. The ANFA-based results are compared with reference fragility curves obtained from the Monte Carlo Simulation Method and the Likelihood Estimation Method. The results show that ANFA closely approximates the Monte Carlo-based fragility curve, with a maximum relative difference of approximately 8%, whereas the corresponding discrepancy for the Likelihood Estimation Method reaches approximately 28%. These findings indicate that ANFA provides a practical and computationally efficient alternative for preliminary nonlinear fragility assessment of wind-excited structural systems.

Analitik Kırılğanlık Analizinin Doğrusal Olmayan Yapısal Sistemlere Genişletilmesi: ANFA Yöntemi

Makale Bilgisi

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Öz

Performansa dayalı rüzgâr mühendisliği, stokastik rüzgâr yüklerine maruz kalan yapısal sistemler için hesaplama açısından verimli kırılğanlık değerlendirme yöntemlerine ihtiyaç duymaktadır. Monte Carlo simülasyonu kırılğanlık eğrilerinin oluşturulmasında yaygın bir referans yaklaşım olmasına rağmen, doğrusal olmayan dinamik sistemlerde çok sayıda zaman tanım alanı analizi gerektirdiğinden yüksek hesaplama maliyeti oluşturabilir. Bu çalışmada, Analitik Doğrusal Kırılğanlık Analizi'nin (ALFA) frekans tanım alanına dayalı tepki tahmini yaklaşımını doğrusal olmayan sistemlere genişletmek amacıyla Analitik Doğrusal Olmayan Kırılğanlık Analizi (ANFA) çerçevesi önerilmektedir. Önerilen yöntem, harmonik ayrıştırma ve frekans tepki fonksiyonlarına dayalı hesaplama verimliliğini korurken, doğrusal olmayan yapısal davranışı plastik moment kapasitesine karşılık gelen kapasite uyumlu eşik yer değiştirme aracılığıyla dikkate almaktadır. Yöntemin uygulanabilirliği, stokastik rüzgâr etkisine maruz bırakılan doğrusal olmayan üç serbestlik dereceli bir kütle-kolon sistemi üzerinde gösterilmiştir. İki doğrulu moment-eğrilik ilişkisi ile temsil edilen sistem için 55–85 m/s aralığında kırılğanlık eğrileri elde edilmiştir. ANFA sonuçları, Monte Carlo Simülasyon Yöntemi ve Olasılıksal Tahmin Yöntemi ile karşılaştırılmıştır. Sonuçlar, ANFA'nın Monte Carlo tabanlı kırılğanlık eğrisine yakın sonuç verdiğini ve maksimum göreceli farkın yaklaşık %8 olduğunu göstermiştir. Olasılıksal Tahmin Yöntemi için bu fark yaklaşık %28'e ulaşmıştır. Bulgular, ANFA'nın rüzgâr etkisindeki doğrusal olmayan yapısal sistemlerin ön kırılğanlık değerlendirmesi için pratik ve hesaplama açısından verimli bir alternatif sunduğunu göstermektedir.

1. INTRODUCTION (GİRİŞ)

Performance-based wind engineering (PBWE) has emerged as a probabilistic design and assessment philosophy for evaluating the safety, serviceability, functionality, and life-cycle consequences of structures subjected to wind hazards [1–4]. Unlike conventional prescriptive wind design, which is mainly organized around code-based load combinations and component-level checks, PBWE seeks to connect wind hazard characterization, structural response, damage states, decision variables, and acceptable risk levels within a unified reliability-oriented framework [1,5–8]. This shift is particularly important for wind-sensitive structures such as tall buildings, towers, slender masts, long-span bridges, and flexible structural systems, for which dynamic amplification, aerodynamic uncertainty, damping variability, and occupant or operational performance limits may govern the design [9–11].

The response of wind-excited structures is strongly influenced by the stochastic nature of atmospheric turbulence. Wind speed, directionality, spatial coherence, gust duration, aerodynamic force coefficients, and structural damping all introduce uncertainty into the demand prediction process [9–12]. Classical wind spectra and stochastic simulation methods have therefore played a central role in wind engineering, enabling wind velocity or force histories to be generated in a statistically consistent manner [11–16]. In this context, time-domain simulations are attractive because they can incorporate nonlinear aerodynamic loading, random phase relationships, and structural nonlinearities directly. However, they often become computationally demanding when repeated analyses are required over multiple wind intensity levels and uncertainty realizations [16,17].

Fragility functions provide a practical probabilistic measure of structural vulnerability by expressing the conditional probability that an engineering demand parameter exceeds a specified limit state for a given intensity measure [18–22]. Although fragility analysis was first widely formalized in earthquake engineering, the same probabilistic concept is now increasingly used in wind engineering to quantify exceedance probabilities associated with serviceability, first yielding, damage initiation, loss of functionality, and collapse-related limit states [1,4,7,8,16,18,20,23]. For wind-excited systems, fragility curves are particularly valuable because they can translate complex stochastic response behavior into compact performance metrics suitable for risk assessment,

comparative design, and decision-making under uncertainty [4,7,8,16,23].

The most direct strategy for developing wind-induced fragility curves is Monte Carlo simulation (MCS), in which a large number of stochastic wind fields are generated and applied to a structural model to estimate the probability of limit-state exceedance [16,17,23]. When the structural model is linear and computationally inexpensive, this approach can be implemented with manageable effort. However, for high-fidelity finite element (FE) models, nonlinear dynamic analysis, inelastic material behavior, geometric nonlinearity, or rare-event probability estimation, brute-force MCS may require thousands or even tens of thousands of nonlinear time-history analyses [16,17,23–25]. Advanced reliability methods such as subset simulation, first- and second-order reliability methods, and likelihood-based or reduced-sample estimation can reduce the number of simulations, but their accuracy may depend strongly on the assumed response model, sampling strategy, limit-state shape, and degree of structural nonlinearity [17,19,20,23,26,27].

This computational challenge is especially critical for nonlinear wind-excited systems. As PBWE moves beyond serviceability-oriented elastic response and toward inelastic performance, collapse assessment, and capacity-based decision variables, the modeling framework must be able to represent yielding, stiffness degradation, redistribution of internal forces, residual deformation, and possible instability mechanisms [24,28,29]. Recent studies on inelastic and collapse-level wind performance demonstrate that nonlinear time-history analysis can capture important physical mechanisms, but also confirm that such simulations impose substantial computational burdens when embedded in probabilistic reliability or fragility assessments [24,28–30]. Consequently, there is a need for methods that retain the physical meaning of nonlinear capacity while reducing reliance on repeated nonlinear dynamic simulations.

Frequency-domain approaches offer an efficient alternative for estimating the dynamic response of wind-excited structures. By decomposing stochastic loads into harmonic components and evaluating structural response through frequency-response functions, the computational effort can be significantly reduced compared with direct time-history analysis [11–15,31,32]. Such methods are particularly effective for linear systems because the principle of superposition allows the total response to be reconstructed from the individual harmonic

responses. Nevertheless, this advantage also defines their main limitation: once the structure enters a nonlinear range, superposition is no longer strictly valid, and the direct application of linear frequency-domain fragility methods becomes questionable [31–33].

Several analytical strategies have historically been proposed to approximate nonlinear random vibration problems, including equivalent linearization, statistical linearization, and response approximation methods [33–35]. These approaches replace a nonlinear system with an equivalent linear representation, usually calibrated in a statistical, energy-based, or response-consistent manner. While such techniques provide valuable theoretical foundations for reducing nonlinear stochastic vibration problems to tractable forms, they are not directly equivalent to a fragility-oriented treatment of nonlinear structural capacity. In particular, for performance assessment, the key challenge is not only to estimate a response statistic efficiently, but also to define a threshold that is mechanically consistent with nonlinear capacity, such as the displacement associated with yield or plastic moment capacity [18–20,33–36].

The present study addresses this gap by proposing an Analytical Nonlinear Fragility Analysis (ANFA) framework for structural systems subjected to stochastic wind loading. The method is conceived as an extension of the Analytical Linear Fragility Analysis (ALFA) concept, which was originally developed for efficient frequency-domain fragility assessment of linear structural systems under wind loading [32]. Instead of explicitly tracing the complete nonlinear response trajectory for every stochastic excitation sample, the proposed framework introduces a capacity-consistent equivalent linear threshold. In this formulation, the frequency-domain response estimation procedure remains computationally efficient, while nonlinear structural behavior is incorporated through a revised limit-state definition associated with the plastic moment capacity of the system.

The main contribution of this study is therefore threefold. First, a generalized analytical framework is formulated to extend frequency-domain fragility assessment from linear to nonlinear structural systems subjected to stochastic wind loading, building directly on the ALFA response-estimation philosophy [32]. Second, a threshold definition is introduced in which the displacement corresponding to plastic moment capacity is used to represent nonlinear structural capacity within an analytically tractable response-estimation

procedure. Third, the proposed ANFA method is validated against reference fragility curves obtained from Monte Carlo simulation and the likelihood estimation method (LEM), thereby allowing its accuracy and computational efficiency to be evaluated against both simulation-based and reduced-sample alternatives [16,23,32].

The applicability of the proposed framework is demonstrated through a nonlinear three-degree-of-freedom (3-DOF) mass-column system subjected to stochastic wind excitation. A bilinear moment-curvature model is used to represent the nonlinear behavior of the structural system, and fragility curves are constructed over a range of mean wind speeds. The results show that the proposed ANFA framework can closely approximate the reference MCS-based fragility curve while requiring substantially fewer nonlinear dynamic analyses. In this way, the study establishes a practical pathway for incorporating nonlinear capacity effects into analytical wind fragility assessment without incurring the full computational cost of brute-force nonlinear simulation.

2. METHODOLOGY: ANFA FRAMEWORK (METODOLOJİ: ANFA Çerçevesi)

2.1. Overview (Genel Bakış)

The Analytical Nonlinear Fragility Analysis (ANFA) framework is proposed as a computationally efficient and accurate methodology for estimating fragility curves of nonlinear structural systems subjected to stochastic wind loading. The methodology builds upon the analytical representation of structural dynamic response in the frequency domain using frequency-response functions, as previously established in the ALFA framework for linear wind-excited systems, and extends its applicability beyond linear systems through a revised treatment of structural capacity [32].

The ANFA framework represents a generalized extension of the previously established Analytical Linear Fragility Analysis (ALFA) methodology [32]. While ALFA relies on the principle of superposition and is therefore restricted to linear structural systems, ANFA extends this analytical framework to nonlinear systems through a capacity-consistent threshold definition that accounts for material and geometric nonlinearities. Rather than explicitly resolving the nonlinear response trajectory, the proposed methodology incorporates nonlinear structural behavior through an equivalent linear representation of structural capacity. As a

result, ANFA preserves the computational efficiency and analytical tractability of ALFA while substantially broadening its applicability to nonlinear dynamic systems. By reducing the dependence on computationally demanding Monte Carlo-based brute-force simulations, the ANFA framework provides a practical and scalable alternative for performance-based wind engineering and structural reliability assessment [32].

The ANFA framework consists of five main steps to achieve an efficient and reliable fragility assessment: (1) high-fidelity structural modeling of the nonlinear system; (2) stochastic generation of representative wind-force time histories; (3) harmonic decomposition of these wind-force samples utilizing Fourier series expansion; (4) frequency-domain estimation of structural response using harmonic response functions; and (5) statistical evaluation of the probability of exceedance using a revised threshold definition consistent with nonlinear structural capacity. The first four steps are intentionally consistent with the ALFA procedure, whereas the fifth step is modified to incorporate nonlinear structural capacity [32].

2.2. Structural System Modeling (Yapısal Sistem Modellemesi)

The structural modeling stage of the ANFA framework aims to establish a generalized representation of nonlinear dynamic structural systems subjected to stochastic wind loading. The formulation presented in this section is independent of any specific structural configuration and is intended to provide a unified basis for subsequent analytical procedures within the ANFA framework.

Nonlinear structural systems are modeled as multi-degree-of-freedom (MDOF) systems, where the dynamic response is governed by the interaction of mass, damping, and stiffness characteristics. The equation of motion for a nonlinear dynamic system can be expressed as:

$$M\ddot{X}(t) + C\dot{X}(t) + F_{int}(X(t)) = F(t) \quad (1)$$

where M and C denote the mass and damping matrices, respectively, $F_{int}(X(t))$ represents the nonlinear internal force vector as a function of displacement, and $F(t)$ is the external wind-induced force vector.

To accurately capture the nonlinear behavior of structural systems, high-fidelity modeling approaches—such as finite element (FE) formulations—are typically employed, as also demonstrated in recent finite element-based studies

involving structural, modal, and harmonic analyses [37,38]. The spatial distribution of mass, stiffness, and boundary conditions is defined in accordance with the structural configuration under consideration. Lumped or distributed mass representations may be adopted depending on the required level of modeling fidelity.

Material nonlinearity is incorporated through a bilinear constitutive model, which provides an efficient approximation of elastoplastic behavior. In this representation, the initial linear elastic response is defined up to the yield point, followed by a secondary linear branch with reduced stiffness to simulate post-yield behavior. This bilinear idealization enables a computationally efficient yet sufficiently accurate characterization of nonlinear structural response, particularly for systems where inelastic deformations influence the dynamic behavior.

The outcome of this stage provides the essential structural properties required for the ANFA framework, including the nonlinear force–deformation relationships and the dynamic characteristics of the system. These properties form the basis for extracting frequency-response parameters, which are central to the ANFA methodology, and enable the transformation of the nonlinear dynamic problem into a form suitable for efficient fragility analysis.

2.3. Stochastic Wind Field Modeling (Stokastik Rüzgar Alanı Modellemesi)

The dynamic excitation acting on structural systems under wind loading is inherently stochastic in nature. Therefore, realistic representation of wind-induced forces is essential for accurate fragility assessment. Within the ANFA framework, stochastic wind fields are modeled through a spectral representation approach, which enables the generation of physically consistent wind-speed time histories, consistent with prior wind fragility applications based on stochastic wind simulations [16,32].

The wind-speed process is characterized in the frequency domain using a power spectral density (PSD) function. In this study, a widely adopted empirical spectrum is utilized to represent the distribution of wind energy across frequencies. Based on the target mean wind speed, stochastic wind-speed samples are generated in the time domain using the spectral representation method, in which the wind process is expressed as a summation

of sinusoidal components with random amplitudes and phases [16,32].

The generated wind-speed samples are subsequently transformed into realistic probability distributions commonly used in wind engineering applications. This transformation ensures that the statistical characteristics of the simulated wind field are consistent with observed wind behavior.

The wind-induced force acting on the structure is then calculated as a function of the instantaneous wind speed. Following standard aerodynamic formulations, the wind force is assumed to be proportional to the square of the wind speed, leading to a nonlinear relationship between the excitation force and the stochastic wind field.

A sufficiently large number of stochastic wind-force time histories are generated to capture the variability of the excitation. These samples serve as the input for the subsequent harmonic decomposition and frequency-domain response estimation stages of the ANFA framework.

2.4. Harmonic Decomposition of Wind Loads (Rüzgar Yüklerinin Harmonik Ayrıştırılması)

The stochastic wind-force time histories generated in the previous stage are inherently irregular and non-periodic in nature. In order to enable an efficient analytical treatment within the ANFA framework, these stochastic excitation forces are decomposed into a series of harmonic components using Fourier series representation.

According to Fourier theory, any sufficiently smooth time-dependent function can be expressed as the summation of sinusoidal functions with different frequencies, amplitudes, and phases. Accordingly, the wind-force time history $F(t)$ can be represented as:

$$F(t) = \frac{a_0}{2} + \sum_{n=1}^{n_f} (a_n \cos(n\omega t) + b_n \sin(n\omega t)) \quad (2)$$

where a_0 , a_n , and b_n are the Fourier coefficients, ω is the fundamental frequency, and n_f denotes the number of harmonic components used in the approximation.

In practice, the number of harmonics is selected to ensure a balance between computational efficiency and representation accuracy. A sufficiently large number of harmonic terms allows accurate reconstruction of the stochastic wind-force signal

while maintaining tractability in subsequent analytical steps.

This harmonic decomposition plays a central role in the ANFA framework, as it enables the transformation of stochastic excitation into a set of deterministic harmonic loads. Each harmonic component can then be evaluated independently within a frequency-domain response analysis.

Although the principle of superposition is strictly valid only for linear systems, the harmonic decomposition remains applicable within the ANFA framework. The resulting harmonic components are utilized within a linear response estimation procedure consistent with the ALFA methodology [32]. It should be noted that this harmonic decomposition is employed solely for response evaluation, while the effects of structural nonlinearity are incorporated separately through the definition of capacity-consistent threshold values.

2.5. Frequency-Domain Response Estimation (Frekans Alanında Tepki Tahmini)

The harmonic decomposition of stochastic wind loads enables the representation of the excitation as a series of deterministic harmonic components. For linear structural systems, the response to each harmonic component can be efficiently evaluated in the frequency domain using frequency-response functions, and the total response can be obtained through the principle of superposition, as implemented in the ALFA framework [32].

Within the ANFA framework, the frequency-domain response estimation procedure remains consistent with the formulation developed for linear systems in ALFA [32]. Specifically, each harmonic component of the wind-induced loading is evaluated independently using frequency-response functions, and the total structural response is obtained through superposition of these harmonic contributions.

It is important to note that, in this stage, the response estimation is performed without explicitly resolving the nonlinear response path of the system. Instead, the analytical formulation follows the same procedure as in the ALFA methodology, ensuring computational efficiency and analytical tractability [32].

This consistency in the response estimation procedure allows the ANFA framework to retain the advantages of frequency-domain analysis, including reduced computational cost and direct analytical evaluation of structural response statistics. The

incorporation of nonlinear structural behavior is addressed separately through the definition of capacity-consistent threshold values, as discussed in the subsequent section.

2.6. Fragility Function Construction (Kırılganlık Fonksiyonunun Oluşturulması)

Fragility functions describe the probability that a structural demand exceeds a predefined limit state under a given level of stochastic loading. Within the ALFA framework, this probability is evaluated by comparing the analytically obtained structural response with a threshold displacement that represents the structural capacity [32].

In the proposed ANFA framework, the fundamental formulation of fragility functions remains unchanged. However, the definition of the threshold displacement is revised to account for nonlinear

structural behavior. The key distinction between the ALFA and ANFA frameworks lies in the definition of the threshold displacement, which is modified to reflect the nonlinear structural capacity.

For nonlinear structural systems, the moment–displacement relationship deviates from linear behavior beyond the yield point and follows a nonlinear trajectory until reaching the plastic moment capacity. As shown in Figure 1, this nonlinear behavior can be approximated by an equivalent linear representation that preserves the displacement corresponding to the plastic moment capacity. In this representation, the nonlinear response path is not explicitly traced; instead, the focus is placed on accurately capturing the ultimate displacement associated with the structural capacity.

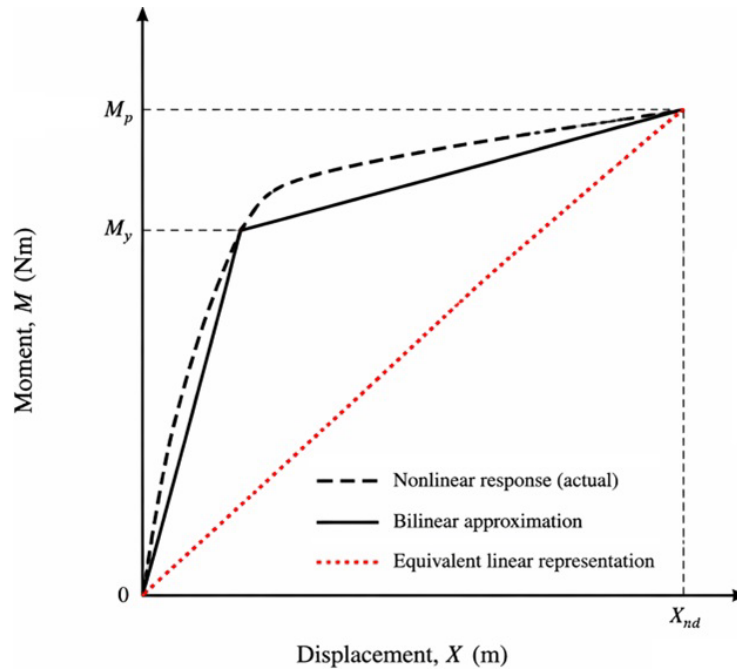


Figure 1. Equivalent linear capacity-based representation of nonlinear moment–displacement behavior. The nonlinear response (dashed line) is approximated by a bilinear model (solid line), and further represented by an equivalent linear system (red dotted line) connecting the origin to the displacement corresponding to the plastic moment capacity. This displacement is used as the threshold value in the ANFA fragility formulation (Doğrusal olmayan moment–yer değiştirme davranışının eşdeğer doğrusal kapasite bazlı gösterimi. Doğrusal olmayan tepki (kesikli çizgi), hem çift doğrusal bir modelle (sürekli çizgi) yaklaşık olarak temsil edilmekte hem de başlangıç noktasını plastik moment kapasitesine karşılık gelen yer değiştirme ile birleştiren eşdeğer doğrusal bir sistemle (kırmızı noktalı çizgi) gösterilmektedir. Bu yer değiştirme, ANFA kırılma formülasyonunda eşik değeri olarak kullanılmaktadır)

Accordingly, the displacement corresponding to the plastic moment capacity is defined as the threshold value in the fragility formulation. This capacity-consistent threshold enables the direct application of the ALFA methodology to nonlinear structural systems without modification of the response estimation procedure [32].

Based on this definition, the probability of exceedance is evaluated as:

$$P_f = P(X_{demand} > X_{capacity}) \quad (3)$$

where $X_{capacity}$ is defined as the displacement corresponding to the plastic moment capacity

obtained from the equivalent linear representation of the nonlinear structural behavior.

This formulation enables the extension of analytical fragility analysis to nonlinear systems by incorporating nonlinear structural effects through the threshold definition rather than through direct nonlinear response simulation. As a result, the ANFA framework achieves a computationally efficient yet physically meaningful approximation of nonlinear fragility behavior. nonlinear simulation.

3. METHODOLOGY: ANFA FRAMEWORK (METODOLOJİ: ANFA Çerçevesi)

3.1. Description of the structural system (Yapısal sistem tanımı)

A nonlinear dynamic three-degree-of-freedom (3-DOF) mass–column system is considered to demonstrate the applicability and accuracy of the proposed methodology. The structural configuration consists of three lumped masses, each

with a magnitude of 2000 kg, located at elevations of 10 m, 20 m, and 30 m, respectively (see Figure 2). As shown in Figure 2(a), the structural system consists of three lumped masses connected through beam-column members, forming an idealized reduced-order representation of a flexible structural system. The adopted bilinear moment–curvature relationship used to represent material nonlinearity is presented in Figure 2(b).

The structural members are modeled as beam elements with a circular cross-section of diameter $D = 0.5$ m and a modulus of elasticity $E = 200$ GPa. Based on these properties, the flexural rigidity of the system is approximately $EI = 615 \times 10^6$ Nm².

This reduced-order three-degree-of-freedom (3-DOF) representation is deliberately adopted to preserve the dominant dynamic characteristics of the structure while enabling an efficient and physically consistent evaluation of its nonlinear response.

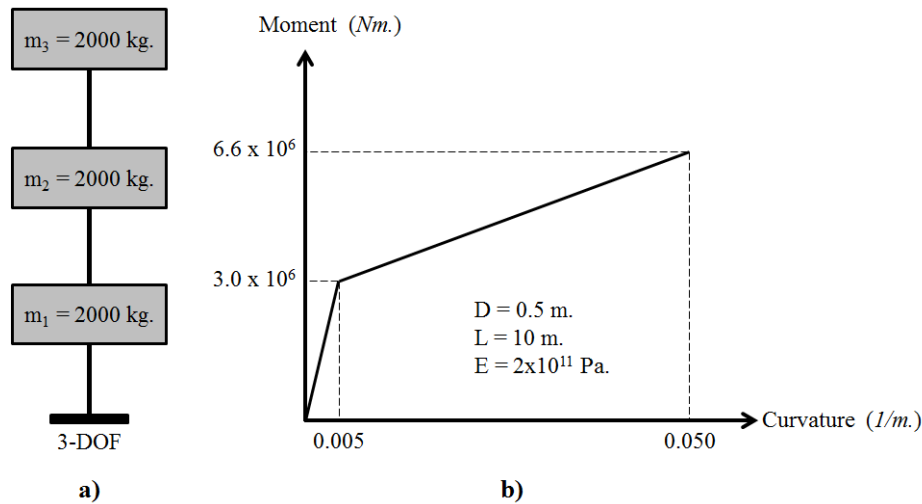


Figure 2. (a) Idealized 3-DOF mass–column system; (b) adopted bilinear moment–curvature relationship representing the nonlinear behavior of the structural system ((a) İdealize edilmiş 3 serbestlik dereceli kütle–kolon sistemi; (b) yapısal sistemin doğrusal olmayan davranışını temsil etmek üzere benimsenen çift doğrusal moment–eğrilik ilişkisi)

3.2. Nonlinear structural modeling (Doğrusal olmayan yapısal modelleme)

The nonlinear structural behavior of the 3-DOF system is modeled within the finite element (FE) software, ADINA 9.1. Beam elements are employed to represent the column members connecting the lumped masses, enabling an efficient representation of the flexural behavior of the system under dynamic wind excitation.

To incorporate structural damping, Rayleigh damping is adopted with a target damping ratio of 15%, corresponding to mass- and stiffness-proportional damping coefficients of $\alpha=1.35$ and

$\beta=0.0077$, respectively. The dynamic characteristics of the structural model are identified through modal analysis, yielding the first three natural frequencies of the system as 0.806 Hz, 5.279 Hz, and 14.180 Hz.

Material nonlinearity is assigned through the bilinear moment–curvature relationship illustrated in Figure 2b. The initial linear branch extends up to the yield moment capacity, defined as $M_y = 3.0 \times 10^6$ Nm. Beyond yielding, the structural behavior is represented using a secondary linear branch with reduced stiffness, extending up to the plastic moment capacity. In this study, the plastic

moment capacity is assumed to be $M_p = 1.2M_y$, corresponding to a simplified representation of the ductile post-yield behavior of the steel structural system.

This bilinear idealization provides a computationally efficient approximation of nonlinear structural behavior while preserving the essential capacity characteristics required for the fragility assessment framework. The resulting FE model serves as the basis for subsequent harmonic response analyses and stochastic wind-loading simulations.

3.3. Stochastic wind loading (Stokastik rüzgar yüklemesi)

The nonlinear 3-DOF structural system is subjected to stochastic wind excitation in order to evaluate its fragility performance under uncertain loading conditions. The wind-speed time histories are generated following the stochastic wind field modeling procedure described in Section 2.3, consistent with previous probabilistic wind fragility studies in which stochastic wind histories were used as the basis for dynamic response and failure-probability estimation [16,23].

For the case study, a total of 1000 stochastic wind-speed samples are generated for each target mean wind speed. The target mean wind speed varies from 55 m/s to 85 m/s with increments of 1 m/s, resulting in 31 different wind-speed levels. These realizations are used to represent the variability of wind loading at each intensity level.

The generated wind-speed time histories are converted into wind-force time histories using the standard aerodynamic force relationship, in which the wind force is proportional to the square of the instantaneous wind speed. The resulting stochastic wind-force samples are then applied to the lumped masses of the 3-DOF system as dynamic excitation forces.

In total, 31,000 stochastic wind-force realizations are generated and used in the fragility assessment. This dataset provides the input basis for both the proposed ANFA-based analytical procedure and the reference nonlinear dynamic analyses used for validation.

3.4. Application of the proposed ANFA framework (Önerilen ANFA çerçevesinin uygulanması)

The proposed ANFA framework is applied to the nonlinear 3-DOF structural system through a

sequence of analytical procedures involving harmonic decomposition and frequency-domain response estimation. The stochastic wind-force samples generated in the previous section are first represented using Fourier series expansion, enabling the decomposition of each irregular excitation history into a set of deterministic harmonic components, following the same analytical response-estimation logic adopted in ALFA [32].

For the harmonic representation, the upper limit of the Fourier expansion is selected as $n_f = 999$, providing sufficient accuracy for reconstructing the stochastic wind-force signals. Accordingly, each generated wind-force sample is represented as a summation of harmonic excitation components and subsequently used for response estimation within the ANFA framework.

To characterize the frequency-domain response of the structural system, a series of harmonic analyses is performed using the FE model described in Section 3.2. A total of 100 harmonic excitation frequencies varying from 0.1 rad/s to 10.0 rad/s with increments of 0.1 rad/s are applied to the structural system. These analyses are used to determine the frequency-response parameters of the structure, namely the dynamic amplification factor and the phase angle, which govern the steady-state response behavior and constitute the core response parameters used in ALFA [32]. The resulting frequency-response characteristics of the structural system are illustrated in Figure 3, which presents the variation of the dynamic amplification factor and phase angle over the investigated excitation frequency range. These frequency-response parameters form the basis for reconstructing the structural response through harmonic superposition within the ANFA framework.

Using these frequency-response parameters, the harmonic response corresponding to each excitation component is evaluated independently. The total structural response is then reconstructed through the superposition of the harmonic contributions, consistent with the ALFA-based analytical formulation [32].

It should be emphasized that the resulting structural demand corresponds to a linearized response representation. Within the ANFA framework, the effects of structural nonlinearity are incorporated separately through the revised threshold definition, which is introduced in the subsequent section.

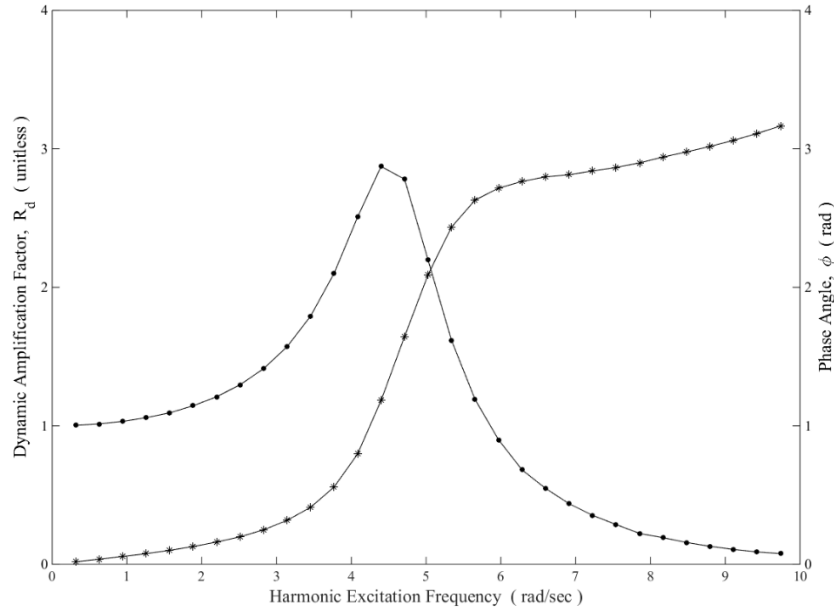


Figure 3. Frequency-response characteristics of the nonlinear 3-DOF structural system, showing the variation of the dynamic amplification factor (line with dots) and phase angle (line with stars) over the investigated excitation frequency range (Doğrusal olmayan 3 serbestlik dereceli yapısal sistemin frekans-tepki özellikleri; incelenen uyarım frekansı aralığında dinamik büyütme katsayısının (noktalı işaretli çizgi) ve faz açısının (yıldız işaretli çizgi) değişimini göstermektedir)

3.5. Definition of capacity and threshold displacement (Kapasite ve eşik yer değişiminin tanımı)

For nonlinear structural systems, the direct comparison between analytically estimated structural demand and nonlinear structural capacity is not straightforward due to the nonlinear moment–curvature behavior beyond yielding. Therefore, a revised threshold definition is introduced to ensure consistency between the response estimation procedure and the structural capacity representation.

In this case study, the plastic moment capacity is adopted as the collapse criterion of the nonlinear structural system. Based on the bilinear moment–curvature relationship illustrated in Figure 2, the structural response is characterized by an initial linear branch up to the yield moment capacity, followed by a post-yield branch extending to the plastic moment capacity.

To enable compatibility with the linear response estimation framework employed in ANFA, the nonlinear structural capacity is transformed into an equivalent linear representation. Consistent with the threshold definition introduced in Section 2.6, the displacement corresponding to the plastic moment capacity is first identified from the nonlinear structural behavior. Subsequently, the initial linear

branch is extended up to the plastic moment level, and the corresponding displacement is redefined as an equivalent threshold displacement, thereby allowing the ALFA-based response-estimation procedure to be retained for the demand side of the fragility calculation [32]. For the present case study, the threshold displacement was determined from a representative nonlinear dynamic analysis conducted within the Monte Carlo simulation procedure. In this analysis, a realistic stochastic wind-force realization was applied to the nonlinear FE model, and the structural response was monitored until the plastic moment capacity, M_p , was reached. The displacement corresponding to this instant was recorded as the nonlinear capacity displacement of the system. This displacement is consistent with the terminal displacement conceptually illustrated in Figure 1 and was adopted as the capacity-consistent threshold displacement in the ANFA formulation. Therefore, the threshold value used in the proposed method was not selected arbitrarily or obtained from a purely elastic assumption; rather, it was derived from nonlinear dynamic response analysis and subsequently introduced into the equivalent linear capacity representation.

Accordingly, the threshold displacement used in the fragility formulation is defined based on this equivalent linear representation rather than the nonlinear displacement trajectory itself. This

revised threshold definition enables the direct application of the ALFA-based response estimation procedure to nonlinear structural systems while preserving the essential capacity characteristics of the structural response [32].

The probability of exceedance is then evaluated by comparing the analytically estimated displacement demand with the revised threshold displacement corresponding to the plastic moment capacity.

3.6. Reference solutions for validation (Doğrulama için referans çözümler)

To evaluate the applicability and reliability of the proposed ANFA framework, two commonly used fragility assessment approaches are employed as reference solutions: The Monte Carlo Simulation (MCS) Method and the Likelihood Estimation Method (LEM). These methods are used to benchmark the fragility predictions obtained from ANFA for the nonlinear 3-DOF structural system, consistent with prior wind fragility studies that used Monte Carlo simulation and likelihood-based fitting for probabilistic performance assessment [16,23].

In the Monte Carlo Simulation Method, the nonlinear FE model described in Section 3.2 is directly subjected to the stochastic wind-force samples generated in Section 3.3. For each target mean wind speed varying from 55 m/s to 85 m/s in increments of 1 m/s, a total of 1000 stochastic wind-force realizations are applied to the nonlinear dynamic structural system. Consequently, 31,000 nonlinear dynamic analyses are performed in ADINA 9.1. The resulting displacement demands are directly compared with the threshold displacement corresponding to the plastic moment capacity in order to compute the probability of exceedance.

In addition to MCM, the Likelihood Estimation Method is also considered as a reference approach due to its widespread use as a computationally efficient fragility assessment tool. In this study, a total of 100 nonlinear dynamic analyses are performed for the implementation of LEM, corresponding to five stochastic wind-force realizations for each target mean wind speed level. The resulting displacement demand samples are subsequently used to estimate the fragility function through statistical inference, following the same general likelihood-based fitting concept previously used for wind-induced fragility curves of steel structural frames [23].

The fragility curves obtained from MCM and LEM are then compared with those predicted by the

proposed ANFA framework to evaluate its accuracy, applicability, and computational efficiency for nonlinear structural systems.

4. RESULTS AND COMPARATIVE ANALYSIS (BULGULAR ve KARŞILAŞTIRMALI ANALİZ)

To evaluate the applicability and reliability of the proposed ANFA framework for nonlinear structural systems, the fragility curve of the nonlinear 3-DOF system is constructed and compared with the corresponding fragility curves obtained using the Monte Carlo Simulation (MCS) Method and the Likelihood Estimation Method (LEM).

Figure 4 presents the resulting fragility curves for the nonlinear structural system subjected to stochastic wind excitation corresponding to mean wind speeds ranging from 55 m/s to 85 m/s. As shown in Figure 4, the fragility curve predicted by ANFA closely follows the reference MCM solution over the investigated wind-speed range. In contrast, the fragility curve obtained using LEM exhibits visibly larger deviations, particularly within the intermediate exceedance probability range.

The maximum relative difference between the fragility curves obtained using ANFA and MCM is approximately 8%, whereas the corresponding discrepancy between LEM and MCM reaches approximately 28%. These results indicate that ANFA provides a substantially more reliable prediction of nonlinear fragility behavior than LEM for the structural system considered in this study.

The relatively small discrepancy between ANFA and MCM can be attributed to the proposed threshold-based treatment of structural nonlinearity. Rather than explicitly resolving the nonlinear dynamic response path, the ANFA framework incorporates nonlinear effects through a revised threshold displacement corresponding to the plastic moment capacity. This capacity-consistent threshold definition enables a meaningful approximation of nonlinear fragility behavior while preserving the efficiency of the analytical response estimation procedure.

Although a certain degree of approximation is introduced through the equivalent linear representation of structural capacity, the resulting prediction accuracy remains within an acceptable range for engineering applications. In particular, the close agreement between ANFA and MCM suggests that the proposed framework is capable of capturing the dominant fragility characteristics of

nonlinear structural systems subjected to stochastic wind loading.

By contrast, the larger deviations observed in LEM indicate that the reduced number of simulations employed in the likelihood-based approach may not sufficiently characterize the uncertainty associated with nonlinear structural response. Consequently, the fragility estimates obtained using LEM exhibit greater discrepancies from the reference nonlinear solution.

It should be noted that the computational advantage of ANFA does not result from reducing the number of stochastic wind-force realizations. In the present study, both the conventional Monte Carlo Simulation Method and the proposed ANFA

framework are evaluated using the same 31,000 stochastic wind-force realizations. The essential difference lies in the type of analysis performed for these realizations. In the conventional Monte Carlo approach, each realization requires a nonlinear dynamic time-history analysis of the FE model, which is computationally demanding. In contrast, ANFA evaluates the response of the same stochastic realizations through frequency-domain response estimation based on harmonic decomposition and frequency-response parameters. Therefore, the computational efficiency of ANFA is achieved by replacing repeated nonlinear dynamic simulations with analytically tractable frequency-domain response calculations, rather than by reducing the probabilistic sample size.

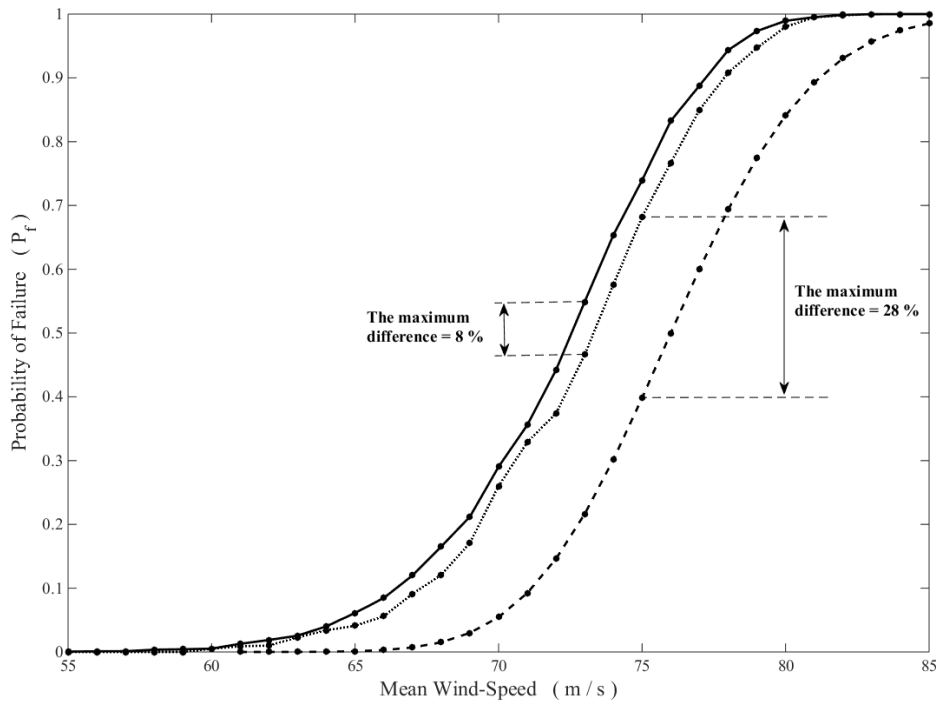


Figure 4. The fragility curves of the non-linear dynamic 3-DOF system using ANFA (solid line), MCM (dotted line), and LEM (dashed line) (ANFA (sürekli çizgi), MCM (noktalı çizgi) ve LEM (kesikli çizgi) kullanılarak elde edilen doğrusal olmayan dinamik 3 serbestlik dereceli sistemin kırılabilirlik eğrileri)

5. DISCUSSION (TARTIŞMA)

The results of this study demonstrate that the proposed ANFA framework provides a reliable and computationally efficient approach for extending analytical fragility analysis to nonlinear structural systems subjected to stochastic wind loading. By introducing a revised threshold definition consistent with nonlinear structural capacity, the methodology enables the direct application of frequency-domain analytical response estimation originally developed for linear systems in the ALFA framework [32]. The most important distinction of the ANFA framework

lies in the treatment of structural nonlinearity. Instead of explicitly resolving the nonlinear dynamic response path through computationally demanding nonlinear time-history simulations, nonlinear behavior is incorporated through a capacity-consistent threshold definition corresponding to the plastic moment capacity of the structural system. This approach enables compatibility between analytically estimated structural demand and nonlinear structural capacity while preserving computational tractability.

The comparative results indicate that the proposed framework achieves acceptable agreement with the reference Monte Carlo Simulation Method. For the nonlinear 3-DOF system investigated in this study, the maximum discrepancy between ANFA and MCM remained approximately 8%, suggesting that the proposed approximation is sufficiently reliable for engineering fragility assessment purposes. Although this discrepancy is greater than that commonly observed for linear systems, the level of agreement remains acceptable considering the substantial reduction in computational demand.

The observed discrepancies between ANFA and MCM can be attributed to the simplified representation of nonlinear structural behavior through an equivalent linear threshold definition. Since the complete nonlinear response trajectory is not explicitly resolved, certain nonlinear dynamic effects may not be fully represented. Nevertheless, the results suggest that the dominant fragility characteristics of nonlinear structural systems can still be captured with sufficient accuracy for practical engineering applications.

It should also be emphasized that the objective of the proposed ANFA framework is not to reproduce the complete nonlinear dynamic response history of the structure. Nonlinear dynamic effects such as stiffness degradation, yielding-induced period elongation, energy dissipation, and path-dependent response may not be fully captured when nonlinear behavior is represented only through a revised capacity threshold. Therefore, ANFA should not be interpreted as a replacement for detailed nonlinear time-history analysis when the full nonlinear response trajectory is required. Instead, the proposed method is intended as a computationally efficient fragility-curve construction framework. By combining frequency-domain response estimation with a properly defined nonlinear capacity threshold, ANFA enables exceedance probabilities to be estimated with substantially lower computational effort than conventional Monte Carlo simulation, which typically requires a large number of nonlinear dynamic analyses. In this sense, the main purpose of ANFA is to retain the essential nonlinear capacity information needed for fragility assessment while avoiding the computational burden of repeatedly solving nonlinear dynamic response histories for all stochastic wind realizations.

Compared with the traditional Likelihood Estimation Method, ANFA demonstrates substantially improved prediction accuracy for the nonlinear structural system considered in this study.

The larger deviations observed in LEM suggest that limited-sample statistical estimation may be insufficient to accurately characterize nonlinear structural fragility under stochastic wind excitation.

It should be emphasized that the objective of this study is not to replace detailed nonlinear dynamic simulations in all applications. Rather, the proposed framework is intended to provide an efficient alternative for preliminary fragility assessment, parametric investigations, and computationally demanding engineering applications where repeated nonlinear simulations may become impractical, extending the practical motivation of ALFA from linear systems toward nonlinear structural capacity assessment [32].

The present study focuses on a nonlinear 3-DOF structural system subjected to stochastic wind loading. Therefore, further studies involving different structural configurations, material nonlinearities, and loading scenarios would be beneficial to evaluate the broader applicability and robustness of the ANFA framework. In particular, future investigations may examine the performance of the proposed methodology for higher-degree-of-freedom systems and alternative nonlinear constitutive relationships.

6. CONCLUSIONS (SONUÇLAR)

This study presents the Analytical Nonlinear Fragility Analysis (ANFA) framework for the efficient fragility assessment of nonlinear structural systems subjected to stochastic wind loading. The proposed methodology extends the previously developed ALFA framework to nonlinear systems through a revised threshold definition consistent with nonlinear structural capacity [32].

The ANFA framework preserves the computational advantages of frequency-domain analytical response estimation while incorporating nonlinear structural effects through an equivalent linear capacity representation. Rather than explicitly resolving the nonlinear response trajectory through computationally demanding nonlinear time-history simulations, the methodology introduces a capacity-consistent threshold displacement corresponding to the plastic moment capacity of the structural system. In this respect, ANFA maintains the response-estimation structure of ALFA while modifying the capacity side of the fragility formulation to address nonlinear behavior [32].

The applicability and reliability of the proposed framework are demonstrated through a nonlinear 3-

DOF structural system subjected to stochastic wind excitation. The fragility predictions obtained using ANFA are compared with those from the Monte Carlo Simulation (MCS) Method and the Likelihood Estimation Method (LEM). The results indicate that ANFA provides good agreement with the reference nonlinear solution, with a maximum relative difference of approximately 8%, while significantly improving computational efficiency compared with conventional nonlinear simulation-based approaches.

The findings of this study suggest that ANFA provides a practical and computationally efficient alternative for preliminary fragility assessment of nonlinear structural systems. In particular, the methodology may be beneficial for engineering applications involving repeated risk evaluations, parametric investigations, and large-scale fragility analyses where nonlinear time-history simulations become computationally expensive.

Although the present study focuses on a nonlinear 3-DOF structural system under stochastic wind loading, the proposed framework establishes a foundation for future applications to more complex structural configurations and alternative forms of structural nonlinearity. Future studies may further investigate the robustness and applicability of ANFA across broader classes of engineering systems and loading conditions.

Although the results of this study demonstrate the potential of ANFA as a computationally efficient framework for preliminary nonlinear fragility assessment, the scope of the present validation should be interpreted with some caution. The proposed method has been demonstrated using a simplified nonlinear 3-DOF structural system subjected to stochastic wind loading. Therefore, further validation is required before the method can be generalized to more complex structural configurations. Future studies should investigate the performance of ANFA for higher-degree-of-freedom systems, different nonlinear mechanisms, alternative constitutive models, and various wind-loading conditions. Such studies would provide a broader assessment of the robustness and applicability of the proposed framework.

Overall, the proposed ANFA framework establishes an efficient pathway for extending analytical fragility assessment beyond linear structural systems while maintaining practical computational requirements.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Cihan ÇİFTÇİ: He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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