



# Study on the Seismic Performance of Jacket-Type Offshore Wind Turbines Based on Self-Resetting Buckling-Restrained Brace

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**Abstract.** Offshore wind power, as a core technology of renewable energy, faces dual challenges from wind loads and seismic forces. Due to their high flexibility and structural complexity, jacket-type offshore wind turbine structures are particularly vulnerable to seismic forces. This paper employs finite element time-history analysis to establish a finite element model of a jacket-type wind turbine, analyzing the dynamic response characteristics of different turbine structures under various seismic conditions. The results indicate that the Self-Resetting Buckling-Restrained Brace (SCBRB) system can significantly improve the seismic performance of jacket structures, reducing both peak displacement and residual deformation. The findings provide new theoretical foundations and engineering references for the seismic design of offshore wind turbines.

**Keywords:** Self-Resetting Buckling-Restrained Brace; Offshore Wind Turbine Jacket; Seismic Performance

## 1 Introduction

As a critical component of offshore wind farms, ensuring the safe operation of large wind turbines is essential for both energy production and extending their service life. However, due to the complexity of the offshore wind farm environment, turbine structures must not only withstand strong wind loads but also respond to occasional seismic forces. In high-vibration environments, jacket structures, due to their long-period characteristics and complex connection joints, are particularly vulnerable, making their seismic performance a potential weak link in the overall system.

In recent years, BRB has emerged as a novel seismic component and has been widely applied in structures such as bridges and supertall buildings. Traditional BRB effectively enhance the hysteretic energy dissipation capacity of structures by suppressing buckling phenomena. However, conventional BRB may experience significant residual deformation under multiple seismic events, which can impact the subsequent functionality of the structure. To address this issue, SCBRB has garnered increasing attention from both academia and industry. SCBRB improves upon traditional BRB by

incorporating a restoring force mechanism, allowing the structure to rapidly return to its initial position after an earthquake, thereby reducing residual deformation [1-3].

This study focuses on a 10 MW four-legged jacket-type offshore wind turbine located in the Bohai Sea as its research object [4-6]. By employing the ABAQUS finite element software, a full-scale model of the turbine's structural framework is constructed. The original components of the structure that are prone to buckling are substituted with BRB and SCBRB elements. A comparative vibration response study is conducted for the jacket-type offshore wind turbine under three distinct seismic motion scenarios before and after the substitution. The primary objective is to offer guidance for the design and research of analogous offshore wind turbine structures.

## 2 Finite Element Model of Offshore Jacket-Type Wind Turbine

### 2.1 Wind Turbine Model

A simplified representation of a four-legged jacket-type offshore wind turbine in the Bohai Sea [7] has been developed using ABAQUS software, referred to as Model FJ1, as illustrated in Figure 1. The nacelle, which weighs a total of 446,036 kg, and the hub, including the blades amounting to 230,667 kg, are modeled as point masses. These are applied as concentrated masses at the top of the tower and the front end of the nacelle unit, respectively. Given that the turbine is located in a sea area with hard clay soil, the interaction between the non-elastic soil and the piles is modeled by extending the mud-line vertically downward to four times the pile diameter, using a method that treats the pile legs as rigidly fixed at the bottom [8].

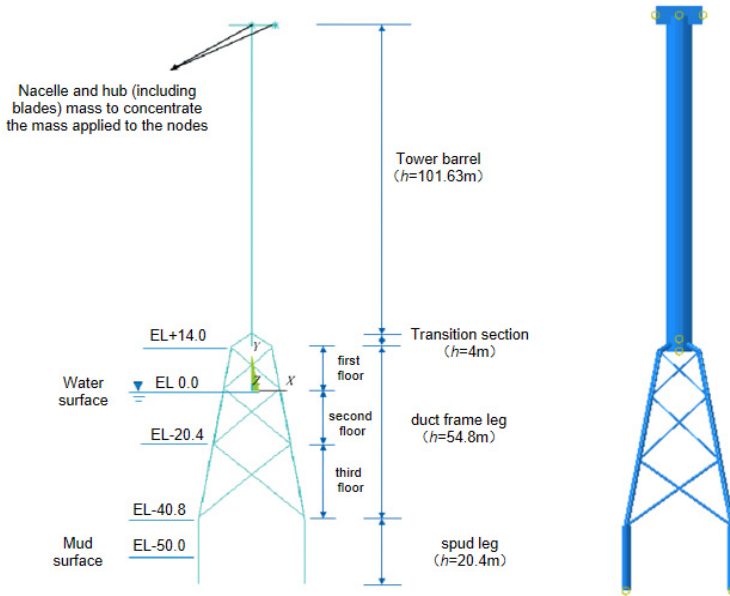
The structure consists of the nacelle, tower, transition piece, jacket structure, and pile legs, arranged vertically from top to bottom. The distance between the hub and the yaw axis is 7.1 meters. Both the tower and transition piece are designed with a tapered profile, featuring a narrower diameter at the top and a wider diameter at the base. The upper distance between the jacket legs is 12m, and the bottom distance is 32m. The four jacket legs are connected by three cross braces of varying sizes in each elevation plane, categorized into three levels from top to bottom: the first, second, and third levels. The four vertical pile legs are arranged in a square distribution. The material used for all structural components is Q345B steel, with material properties as listed in Table 1. Specific component dimensions are provided in Table 2.

Table 1. Material properties of steel

elasticity modulus (GPa)	Poisson's ratio	Material density (kg·m-3)	Yield stress (MPa)	tangent modulus (MPa)
206	0.3	7850	345	610

**Table 2.** Section dimension parameter

Component name	Tower barrel	Transition section	duct frame leg	Brace (First floor)	Brace (Second floor)	Brace (Third floor)	spud leg
Tube radius	2.750~3.981	0.8~1.6	0.825	0.300	0.320	0.420	1.400
Wall thickness	0.020~0.036	0.070	0.045	0.024	0.026	0.030	0.055

**Fig. 1.** Finite element model

## 2.2 Model Design

### (1) Model Parameters.

This study includes three different full-scale wind turbine structure models, as shown in Table 3. Model FJ1 represents the original wind turbine structure, FJ2 is the model where the second-level diagonal braces of FJ1 are replaced with Buckling-Restrained Braces (BRB) having a yield strength of 100 MPa, and FJ3 is the model where the BRBs in FJ2 are further enhanced with a self-resetting system (SC) to create the final wind turbine structure. The principle for replacing conventional members with Buckling-Restrained Braces (BRB) is that the bearing capacity of the BRBs must be calculated to match the bearing capacity of the original conventional members [3]. In the FJ3 turbine structure, the second-level diagonal braces are equipped with a self-resetting system (SC), designed based on the Self-Resetting Buckling-Restrained Brace (SCBRB) system described in [3], with a reset ratio of 1.

**Table 3.** Section dimension parameter

Model name	Type of Second floor brace	Yield strength(MPa)	Area of section (mm <sup>2</sup> )	SC Prepressure(kN)
FJ1	Ordinary brace	345	50152.39	/
FJ2	BRB	100	192250.81	/
FJ3	SCBRB	100	192250.81	14264.72

In the ABAQUS finite element models of the three wind turbine structures, the Buckling-Restrained Braces (BRBs) are simulated using T3D2 truss elements. During mesh generation, only a single mesh is applied to achieve the desired buckling-restraining effect. The self-resetting system is modeled using nonlinear springs. For other components of the wind turbine structure, B31 beam elements are used for simulation.

## (2) Modal Analysis.

Modal analysis is conducted on the FJ1, FJ2, and FJ3 wind turbine structures. The first seven modes and the corresponding natural frequencies of the three structures are shown in Table 4. It can be observed that the first two frequencies of the FJ1, FJ2, and FJ3 structures change slightly. Since low-yield-point steel is used for the buckling-restrained braces, a larger cross-sectional area is required to maintain the same load-carrying capacity as the original supports. This results in an increase in the structural stiffness, and consequently, the natural frequencies of the structures also increase. Furthermore, the FJ3 structure, which incorporates a self-resetting system into the BRBs of the FJ2 model, exhibits an increase in both structural stiffness and frequency.

**Table 4.** First seven natural frequencies of the structure

Order number/order	1	2	3	4	5	6	7
FJ1	0.19409	0.19419	1.5594	1.5677	2.4759	2.4881	2.7679
FJ2	0.20403	0.20415	1.4779	1.4834	2.4713	2.4767	2.6200
FJ3	0.20411	0.20423	1.4587	1.4638	2.4469	2.4618	2.5852

## 2.3 Seismic Excitations

This study investigates the dynamic behavior of jacket-type wind turbine structures under rare seismic events. The offshore wind turbine site has a seismic design intensity of level 8, corresponding to a peak ground acceleration (PGA) of 0.20g. For the analysis, three real-world seismic records—Taft, El-Centro, and Cholame—are employed as loading scenarios, as illustrated in Fig.2. The peak acceleration of all three seismic waves is scaled to 400 gal. For the model analysis, the three seismic waves are applied separately to the three wind turbine structures in the X-direction (as shown in Figure 1) for time-history analysis. Displacement and acceleration response data are extracted and compared at the top of the tower, the top of the jacket structure, and the top of the pile legs.

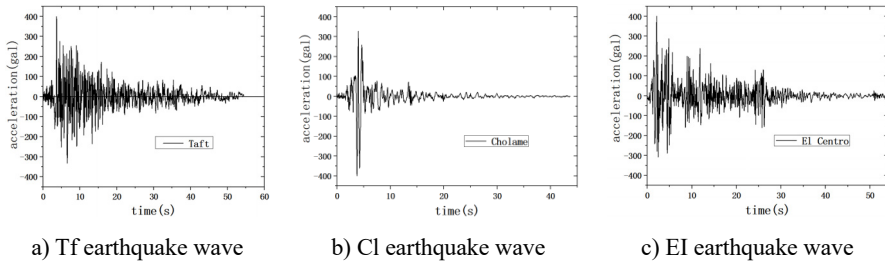


Fig. 2. Seismic recording

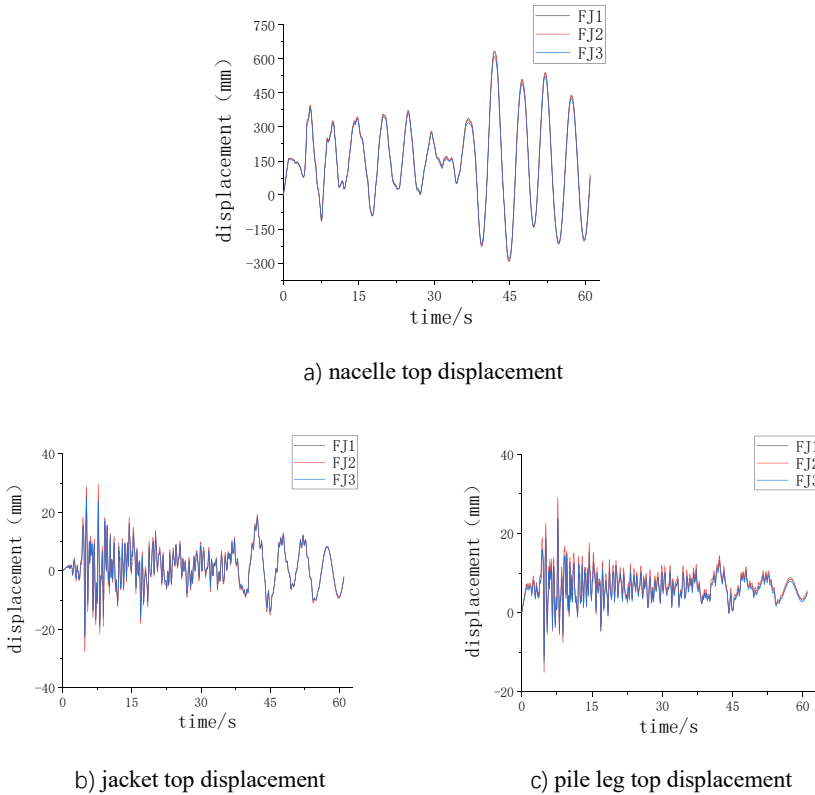
### 3 Computational Results

#### 3.1 Results Under the Taft Earthquake Wave

The dynamic response of the jacket-type wind turbine structure under the Taft earthquake wave (as shown in Table 5 and Fig.3) reveals that, under the influence of the Taft wave in the X-direction, the peak displacement reduction of the FJ3 structure (represented as the percentage of reduction in seismic response compared to the original structure) reaches a maximum of 17.59%. Compared to the FJ1 structure, the FJ2 structure, where the second-level braces are replaced with steel having a yield strength of 100 MPa, begins to yield and dissipate energy earlier. This results in a reduction of the brace stiffness, leading to a decrease in the overall stiffness of the turbine structure. Therefore, the seismic forces acting on the structure are reduced. Furthermore, the FJ3 structure, which incorporates the self-resetting system, shows a significant reduction in lateral displacement compared to the FJ2 structure. Thus, under the Taft earthquake wave, the FJ3 wind turbine structure demonstrates the best vibration reduction performance. The time-history curves for displacement and acceleration are shown in Fig.3.

Table 5. Peak of structural dynamic response

Structural Type	Nacelle Top Displacement	Jacket Top Displacement	Pile Leg Top Displacement
FJ1	633.77	23.73	23.67
FJ2	630.87	29.54	29.11
FJ3	609.55	25.16	23.99



**Fig. 3.** Dynamic behavior of the structure under the Taft earthquake wave

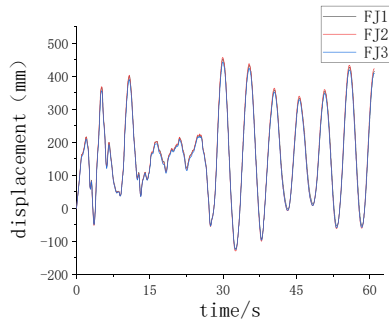
### 3.2 Results Under the EI-Centro Earthquake Wave

The dynamic response of the jacket-type wind turbine structure under the EI-Centro earthquake wave (as shown in Table 6 and Fig.4) indicates that, under the influence of the EI-Centro wave in the X-direction, the peak displacement and peak acceleration reduction of the FJ3 structure achieves a maximum of 15.02%, with the best vibration reduction observed at the top of the pile legs. By incorporating the self-resetting system into the BRB braces of the FJ2 structure, the peak displacement at the top of the jacket is reduced from 44.11 mm to 38.94 mm, resulting in a vibration reduction effect of 11.72%. The maximum displacement at the tower top reduces to 442.81 mm from 457 mm, resulting in a 2.12% decrease in vibration. Overall, when subjected to the EI-Centro wave in the X-direction, the FJ2 structure exhibits marginally greater displacement compared to the FJ1 structure. This indicates that the vibration reduction control for the jacket-type wind turbine structure is less effective than expected. The advantage of the low-yield-point steel BRB braces in energy dissipation is not fully

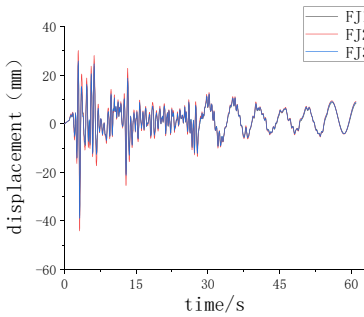
realized in this case, and instead, the structure absorbs more seismic energy. The time-history curves of structural displacement are shown in Fig.4.

**Table 6.** Peak of structural dynamic response

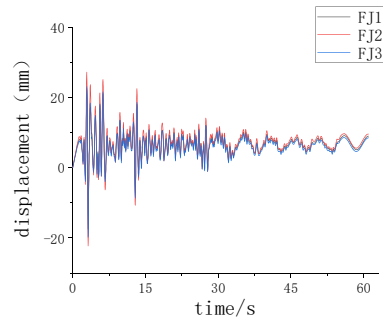
Structural Type	Nacelle Top Displacement	Jacket Top Displacement	Pile Leg Top Displacement
FJ1	452.40	37.69	22.59
FJ2	457.00	44.11	27.23
FJ3	442.81	38.94	23.14



a) nacelle top displacement



b) jacket top displacement



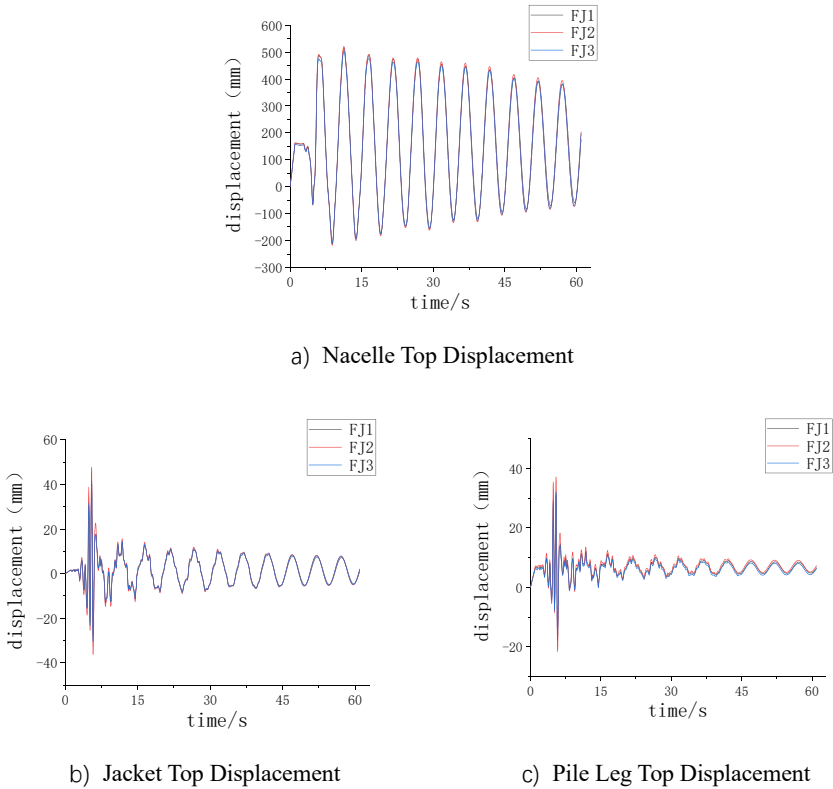
c) pile leg top displacement

**Fig. 4.** Dynamic behavior of the structure under the EI earthquake wave

### 3.3 Results Under the Cholame Earthquake Wave

The vibration reduction effect of the jacket-type offshore wind turbine structure under the Cholame earthquake wave in the X-direction was analyzed, with displacement results at key locations of the turbine structure shown in Table 7. The results indicate that, similar to the analysis under the EI-Centro wave, the dynamic response of the FJ2

structure is slightly increased compared to the FJ1 structure, which is not favorable for vibration control. The FJ3 structure, which incorporates the self-resetting system, exhibits the best vibration control effect, with a significant reduction in the dynamic response compared to the original structure. For example, under the Cholame wave in the X-direction, the peak displacements at the top of the tower, the top of the jacket structure, and the top of the pile legs for the FJ3 structure are reduced by 2.51%, 12.1%, and 13.72%, respectively. This reduction effectively lowers the amplitude of structural vibrations during the seismic event, contributing to the protection and safety of the wind turbine structure. The time-history displacement curves are shown in Fig.5.



**Fig. 5.** Dynamic behavior of the structure under the Cl earthquake wave

**Table 7.** Peak of structural dynamic response

Structural Type	Nacelle Top Displacement	Jacket Top Displacement	Pile Leg Top Displacement
FJ1	516.82	40.44	31.12
FJ2	520.66	47.67	37.17
FJ3	503.81	41.90	32.07

## 4 Conclusions

This study uses finite element time-history analysis to investigate the seismic performance of SCBRB in jacket-type offshore wind turbines. The results show that under rare seismic conditions, the implementation of SCBRB can effectively reduce seismic responses and residual deformations. The wind turbine structure with SCBRB in this study demonstrates a vibration reduction effect of up to 17.59%. Although the initial investment in SCBRB is relatively high, its superior seismic performance and rapid post-earthquake recovery capability can significantly reduce operation and maintenance costs over the entire lifecycle. This is especially beneficial in extreme environmental conditions, making it highly applicable for offshore wind turbines. Future research could further explore the optimization and integrated design methods for the ducted fan structure with SCBRB, providing the design parameters for the SCBRB configuration.

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