A Numerical Analysis for Stress Concentration of Openings in Offshore Tubular Steel Tower under Design Loading Condition

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설계하중조건에 따른 해상풍력 강재타워 출입구에 발생되는 응력집중에 대한 해석적 연구

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Abstract This study investigates the stress concentration factor of a door opening of an offshore tubular steel tower. The tubular steel tower is subjected to eight (8) different load combinations which are deemed to be normal and abnormal operating cases for the ultimate limit state and serviceability limit state. Analytical method using parametric equations and numerical method of finite element are used to analyze the stress components as well as any translations or rotations where the flow of stress is interfered with. A finite element program, ABAQUS, is used for the numerical method analysis. Trends of the stress concentration in the localized area near the opening are studied, and points of interest are defined for comparison among three different cases of tubular steel tower: without door and without reinforcement; without door opening and with reinforcement; and with door opening and with reinforcement. Findings are tabulated and shown in illustrative charts, and conclusions are made.

요 약 본 연구는 해상풍력 강재타워의 출입문에 발생되는 응력집중에 대해 상세히 기술하고 있다. 원형강재 풍력타워에는 8종류의 하중조합이 작용하며 그 하중조합은 극한한계상태와 사용한계상태를 고려한 정상 및 이상시 운영상태를 고려하고 있다. 유한요소해석 및 변수연구에 범용해석프로그램인 ABAQUS를 사용하였으며 응력값이 변화되는 곳을 고려하여 변위 및 응력을 검토하였다. 출입문 주변의 응력집중현상을 비교분석하기 위하여 출입문이 없는 경우, 출입문은 없으나 보강재가 있는 경우, 출입문 및 보강재가 모두 적용된 경우로 구분하여 해석연구를 수행하였다. 분석내용은 본문에 자세히 기술하고 있으며, 해석결과 응력집중계수 평균값은 1.47, 최대값은 1.81로 분석되었다.

Key Words : Sress Concentration, Door Opening, Wind Turbine, Tubular Steel Tower

1. Introduction

Wind turbines are of particular importance as demand in global energy increases. These wind turbine towers are configured differently; it could be a three-dimensional truss or a lattice tower, a steel-reinforced concrete tower, a guyed steel tubular tower or a steel tubular tower, the most common and preferred type in use. These steel tubular towers are designed by the factors of fatigue strength regularly for 20 years of operation, of stiffness according to its vibrational response, of buckling strength which is

usually the determining factor in design calculation, and of static load or breaking load as determined by tower head weight, tower's self-weight and aerodynamic rotor thrust.

In the case of tubular steel towers, openings are necessary to serve as access for maintenance and service done inside the tower. This discontinuity or change in geometry may result in high stress gradients, also known as the phenomenon of stress concentration. The stress concentration factor, K_t, quantifies the stress ratio between the sample section with the opening and the same sample section without the opening. When a material is subjected to a loading over its area, distribution of this loading is uniform; but with an opening, area is reduced. Accordingly, stress concentrates and becomes dense near the hole. A study by Jørgensen[1] found that a stress concentration factor of 1.8 is characteristic and typical in a door opening for a tubular steel tower. Furthermore, a guideline by DNV/DTU Wind Energy[2] states that the determinants of stress concentration in an opening of a wind turbine are dependent heavily on how the door flange is carried out, on how the flange is aligned with the tower wall, on to what extent the door frame replaces the missing tower and on the local stability of the door region.

The effects of openings on the shell strength have been extensively studied. Examples of studies investigating the strength of axially loaded shells with openings are those of Starnes[3], Toda[4] [5], Han et al.[6] and Shariati and Rokhi[7]. On the other hand, examples of studies investigating the strength of shells with openings under bending are of Yeh et al.[8] and Poursaedi et al.[9]. Lastly, a study similar to a moderate extent to this study is that of Golling's[10]. Golling investigated stress distribution and buckling resistance of the door opening for lower tower sections.

This study focuses on a door opening of a wind tower where it is found to induce stress concentrations. With this study, the stress concentration and the factors responsible in tubular steel towers will be determined. The findings can be useful to structural engineers and wind turbine manufacturers as a reference in designing openings.

2. Finite Element Modeling

2.1 General

The model wind turbine tower that is used in this study is shown in Figure 1. It is similar to the geometrical characteristics of a 3 megawatt towers encountered in field practice. The model tower has a hub height of 80.9 m and a rotor diameter of 90 m. The finite element program, ABAQUS, was used to model the wind turbine using S4R elements for the tubular tower and S8R elements for the door opening due to its shell thickness. Cylindrical shell of the tower was divided according to the size of the diameter, resulting to twenty-seven courses, labeled from C1 to C27, and four flanges, labeled from F1 to F4. Table 1 shows the wind tower's geometrical configuration of every course and flange. These characteristics are configured in a way that the structure remains in the elastic region throughout the analysis. S355 structural steel with a modulus of elesticity of 210 GPa and Poisson's ratio of 0.3, is the material used in modeling for both tubular steel shell and door reinforcement of the tower. Yield strength varies from 345 MPa according to shell thickness. Twenty-six points of interest are defined within the immediate area of the opening as shown in Figure 1(b). These points are chosen because these points are any of the three: point of intersection, or middle point of a long surface, or a slender pointed end. From these points of interest, columns ① to ⑦ and rows Ⓐ to Ⓗ are established for convenience. All rows are horizontal and only column ④ is vertical. Other columns are modified so as to accommodate and associate other points.

[Table 1] Tower Dimensions

Course/Flange No.	Height (mm)	thickness (mm)	Diameter (mm)
F4	370	16	2300
C27	2300	16	2450
C26	2925	16	2489
C25	2925	16	2528
C24	2920	16	2567
C23	2920	16	2606
C22	2920	16	2645
C21	2920	17	2684
C20	2915	18	2722
C19	2915	19	2761
C18	2915	21	2800
F3	280	21	2800
C17	2875	21	2866
C16	2875	21	2933
C15	2870	22	2999
C14	2870	22	3065
C13	2870	23	3131
C12	2865	23	3197
C11	2865	24	3264
C10	2865	24	3330
C9	2865	24	3396
C8	2865	26	3462
F2	360	26	3462
C7	2695	26	3560
C6	2695	26	3659
C5	2695	26	3757
C4	2695	26	3855
C3	2690	26	3954
C2	2690	40	4052
C1	2690	40	4150
F1	180	40	4150

2.2 Geometrical Characteristics of Door Opening and Different Cases

The door is elevated at 0.6 meter from the platform or at the foot of the bottom flange. It stands at a height of 2.55 m with thickness of 0.175 meter. Arrangement of door frame and opening is semi-elliptical at both ends with a rectangular middle portion. Detailed dimensions is shown in Figure 1(c). Three different cases of tubular steel tower were modeled: Case I is a case without door and without reinforcement; Case II is a case without door opening and with reinforcement; and Case III is a case with door opening and with reinforcement. The reinforcement is defined having a door frame of thickness 0.175 meter; the without reinforcement, on the other hand, is defined having the thickness of door frame similar to that of its

surrounding tubular steel shell, precisely 0.04 m. The case with reinforcement is modeled to have an element type of S4R, a general-purpose shell; while the case without reinforcement is modeled as S8R, which is appropriate for thicker shells.
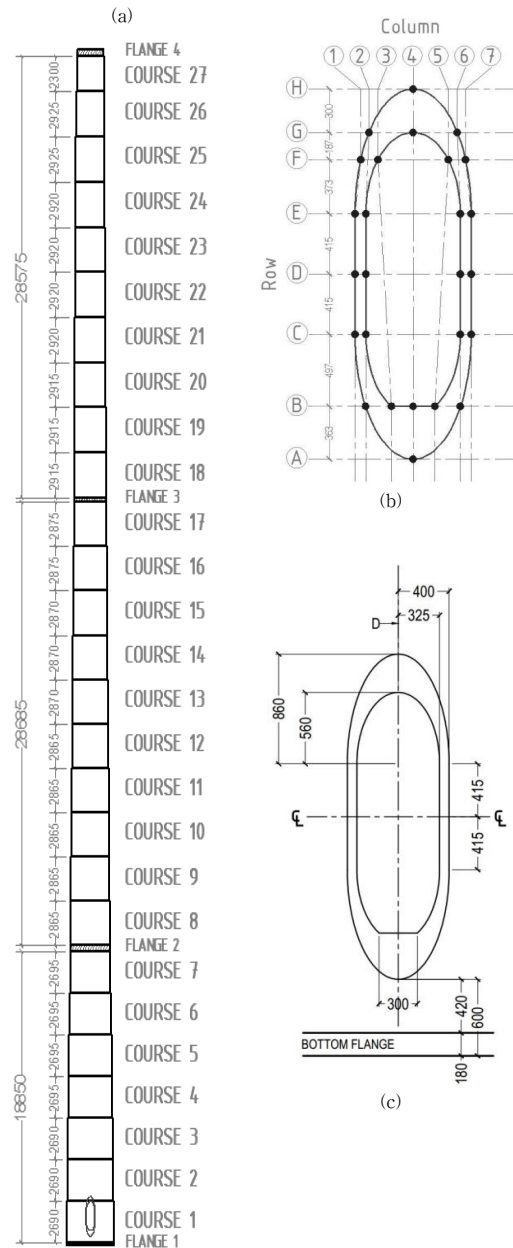
[Fig. 1] Tower Configuration: (a) Tower (b) Points of Interest (c) Dimensions (mm)

2.3 Loading and Boundary Conditions

The tubular steel tower is subjected to eight different load combinations which are deemed to be normal and abnormal operating cases for the ultimate limit state(ULS) and serviceability limit state(SLS). CN-1 until CN-6 are loading combinations that satisfy the ULS, whill CN-7 and CN-8 satisfy the SLS. These load combinations are shown in Table 2 and are applicable in two different state of the wind tower: wind turbine in operation (power production) and parked wind turbine (idling or standing still). Moreover, the load factors are applicable to all types of offshore structures which qualify to normal safety class as per DNV[11].

There are five types of load considered on this study: dead load(DL), tower load(TL), rotor thrust load, wind load and wave load. Dead load comprises of nacelle, hub including nose cone, rotor blades, gearbox, generator systems and oil. Summary of dead load list including its weight used in the analysis is shown in Table 3. Tower load comprises of the tubular steel shell, stiffeners, flanges and etc. Summary of tower load list including its weight is shown in Table 4. For wind load, basic wind velocity is 42.5 m/s as recommended in offshore structures. Door opening is situated on the compression, or on the opposite side of the tubular steel tower from where the wind is coming from. Peak velocity pressure $q_{p(z)}$, as well as external wind pressure we and internal wind pressure w_i, are calculated using BSI[12] and distributed around the shell circumference as shown in Figure 2. Table 5 summarizes the pressure each course and flange is enduring. Lastly, wave load is only considered from Flange 1 until Course 3 with a total wave load of 220.21 kN.

Dead load and a rotor thrust force of 21.08 kN are applied at the center tip of Flange 4, and is transferred onto the upper edges of the same course through an MPC constraint. An identical approach of using MPC constraint is used at the bottom of the cantilever tubular steel tower. The reference point of the constraint is found on the bottom of Flange 1 and has an enacted boundary condition. Subsequently, the tower model is subjected to aforementioned loadings. Static linear perturbation of direct method is used for analysis. Finally, principal(σ_p), hoop(σ_h) and axial (σ_a) stresses are extracted from the results.

[Table 2] Load Cases and Combinations

Comb. Number	Description				Limit Status
	Category G (Permanent)		Category E (Environmental)		
	DL	TL	Wind L	Wave L	
CN-1	1.00	1.00	1.35	1.35	ULS-Normal
CN-2	0.90	0.90	1.35	1.35	ULS-Normal
CN-3	1.00	1.00	1.53	1.53	ULS-Normal
CN-4	1.00	1.00	1.10	1.10	ULS-Abnormal
CN-5	0.90	0.90	1.10	1.10	ULS-Abnormal
CN-6	1.00	1.00	1.24	1.24	ULS-Abnormal
CN-7	1.00	1.00	1.00	1.00	SLS-Normal
CN-8	1.00	1.00	1.00	1.00	SLS-Abnormal

[Table 3] Dead Load List

No.	Description	Weight (kN)	
1	Nacelle	686.47	
2	Hub inc. Nose Cone	215.75	
3	Rotor Blade	200.06	
4	Gearbox & Drivetrain	78.45	1222.28
5	Generator Systems	39.23	
6	Oil	2.33	
Total			1222.28

[Table 4] Tower Load List

No.	Description	Weight (kN)	
1	Shell: t=16mm	170.22	
2	Shell: t=17mm	32.22	
3	Shell: t=18mm	34.54	
4	Shell: t=19mm	36.98	
5	Shell: t=21mm	130.11	
6	Shell: t=22mm	92.60	1372.81
7	Shell: t=23mm	100.93	
8	Shell: t=24mm	166.13	
9	Shell: t=26mm	388.42	
10	Shell: t=40mm	220.66	
11	Stiffener rings	19.61	23.54
12	Door stiffeners & frame	3.92	
13	Top flange	3.92	
14	Middle flange 1	17.65	
15	Middle flange 2	19.61	94.69
16	Bottom Flange	39.23	
17	Anchor ring	14.28	
18	Bolts	7.85	39.23
19	Anchors	31.38	
20	Miscellaneous	14.71	14.71
Total			1544.98

[Table 5] Wind Pressure Calculation

No.	Height (m)	$q_{p(z)}$ (kPa)	w_e (kPa)	w_i (kPa)
F4	77.300	4.7896	3.506	−1.9
C27	76.930	4.7860	3.503	−1.9
C26	74.630	4.7633	3.487	−1.9
C25	71.705	4.7334	3.465	−1.9
C24	68.780	4.7023	3.442	−1.9
C23	65.860	4.6701	3.419	−1.9
C22	62.940	4.6365	3.394	−1.9
C21	60.020	4.6014	3.368	−1.8
C20	57.100	4.5648	3.341	−1.8
C19	54.185	4.5264	3.313	−1.8
C18	51.270	4.4860	3.284	−1.8
F3	48.355	4.4435	3.253	−1.8
C17	48.075	4.4393	3.250	−1.8
C16	45.200	4.3947	3.217	−1.8
C15	42.325	4.3474	3.182	−1.7
C14	39.455	4.2972	3.146	−1.7
C13	36.585	4.2434	3.106	−1.7
C12	33.715	4.1856	3.064	−1.7
C11	30.850	4.1232	3.018	−1.6
C10	27.985	4.0552	2.968	−1.6
C9	25.120	3.9805	2.914	−1.6
C8	22.255	3.8975	2.853	−1.6
F2	19.390	3.8040	2.785	−1.5
C7	19.030	3.7913	2.775	−1.5
C6	16.335	3.6891	2.700	−1.5
C5	13.640	3.5700	2.613	−1.4
C4	10.945	3.4271	2.509	−1.4
C3	8.250	3.2475	2.377	−1.3
C2	5.560	3.0040	2.199	−1.2
C1	2.870	2.6153	1.914	−1.0
F1	0.180	1.2485	0.914	−0.5
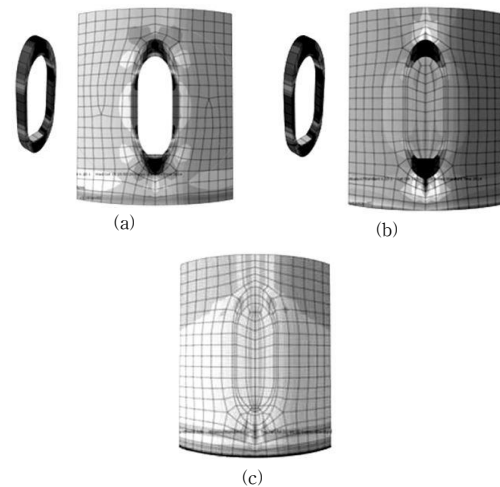
[Fig. 3] FEA Results (a) Case I (b) Case II (c) Case III
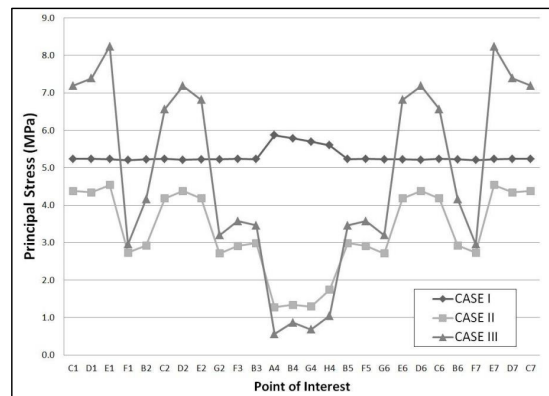
[Fig. 4] Principal Stresses at Points
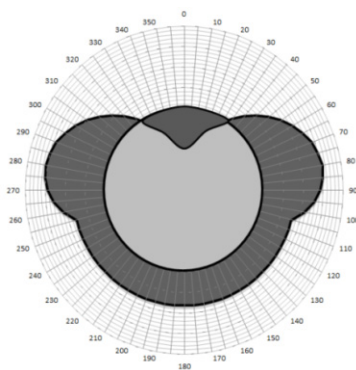
[Fig. 2] Wind Pressure Distribution

3. Finite Element Analysis

Figurative illustration and comparison of principal stresses at different points of interest is shown in Figures 3, 4 and Table 6. As anticipated, Case I has almost uniform principal stresses excluding the variable stresses at Column ④. The result is prospective since the door opening is on the compression side. Contrariwise, both Case II and Case III have irregular flow of stresses. The upper and lower end of the door opening exhibited strong tolerance to stress concentration, while the sides of the opening endured most stress concentration. This denotes that
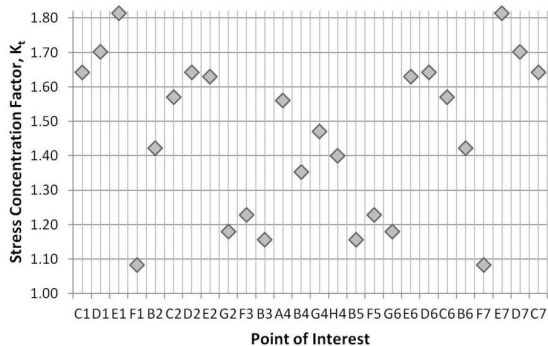
circumferential or hoop stress plays the more crucial factor contrary to axial stress. This is most evident in Case III which has the greatest principal stress at the sides of its opening, specifically located at rows Ⓒ, Ⓓ and Ⓔ.

[Table 6] Principal, Hoop and Axial Stresses around the Opening (Unit: MPa)

Point	Case I			Case II			Case III		
	σ_p	σ_h	σ_a	σ_p	σ_h	σ_a	σ_p	σ_h	σ_a
Ⓒ1	5.23	-3.82	5.23	4.38	-0.03	-4.28	7.19	-0.03	-5.18
Ⓓ1	5.23	-3.82	5.23	4.34	-0.02	-4.24	7.39	-0.00	-5.39
Ⓔ1	5.23	-3.82	5.23	4.54	0.01	-4.33	8.24	-0.02	-6.20
Ⓕ1	5.21	-3.82	5.23	2.73	0.16	-2.67	2.96	0.23	-3.41
Ⓑ2	5.22	-3.82	5.23	2.93	-0.08	-2.79	4.16	-0.08	-4.29
Ⓒ2	5.24	-3.82	5.23	4.18	-0.08	-4.14	6.57	-0.19	-5.28
Ⓓ2	5.21	-3.82	5.23	4.38	-0.03	-4.28	7.19	-0.02	-5.18
Ⓔ2	5.23	-3.82	5.23	4.18	-0.07	-4.08	6.81	-0.16	-5.20
Ⓖ2	5.24	-3.82	5.23	2.71	0.15	-2.65	3.20	0.37	-3.89
Ⓕ3	5.23	-3.82	5.23	2.91	-0.09	-2.78	3.58	0.10	-4.11
Ⓑ3	5.23	-4.31	-1.36	2.99	0.01	-3.01	3.46	0.29	-4.36
Ⓐ4	5.87	-5.73	-9.55	1.28	-0.74	-0.98	0.56	-0.49	-0.29
Ⓑ4	5.79	-5.56	7.83	1.34	0.12	-0.27	0.87	2.10	1.23
Ⓖ4	5.70	-5.23	7.83	1.29	-0.77	-0.90	0.69	-0.39	-0.55
Ⓗ4	5.60	-4.41	7.65	1.75	-0.65	-1.18	1.05	-0.86	-1.32
Ⓑ5	5.28	-4.31	-1.36	2.99	0.02	-3.01	3.46	0.29	-4.36
Ⓕ5	5.24	-3.82	5.23	2.91	-0.09	-2.78	3.58	0.10	-4.11
Ⓖ6	5.22	-3.82	5.23	2.71	0.15	-2.65	3.20	0.37	-3.89
Ⓔ6	5.23	-3.82	5.23	4.18	-0.07	-4.08	6.81	-0.16	-5.20
Ⓓ6	5.21	-3.82	5.23	4.38	-0.03	-4.28	7.19	-0.02	-5.18
Ⓒ6	5.24	-3.82	5.23	4.18	-0.08	-4.14	6.57	-0.19	-5.28
Ⓑ6	5.28	-3.82	5.23	2.93	-0.08	-2.79	4.16	-0.08	-4.29
Ⓕ7	5.21	-3.82	5.23	2.73	0.16	-2.67	2.96	0.23	-3.41
Ⓔ7	5.23	-3.82	5.23	4.54	0.01	-4.33	8.24	-0.020	-6.20
Ⓓ7	5.24	-3.82	5.23	4.34	-0.02	-4.24	7.39	-0.001	-5.39
Ⓒ7	5.24	-3.82	5.23	4.38	-0.03	-4.28	7.19	-0.03	-5.18

[Fig. 5] Stress Concentration

The stress concentration factor, K_t, is arithmetically calculated as the quotient of principal stress at Case III to corresponding reference stress at Case II. Out of twenty-six points of interest, the average K_t, is 1.46; middle value or median is 1.52; factor that is repeated most often is 1.6; lowest and highest factors are 1.082 and 1.814, respectively(Fig. 5). This signifies that for a model wind turbine tower, there is a stress increase of at least 8.2% at locations Ⓕ1 and Ⓕ7, and at most 81.4% at locations Ⓔ1 and Ⓔ7. On average, stress increase in the immediate area of the door opening is 45%. Figure 5 displays stress concentration factors at points of interest. Furthermore in observation, principal stresses at points of interest located at the Column ④ of Cases II and III are relatively small.

Associating Cases I and II, the utilization of reinforcement has decreased the principal stresses at all points of interest. Most notably, the decrease is at its highest at Column ④ from 68.82% up to 78.27%, and the decrease at its lowest at Columns ① and ⑦ from 13.13% up to 16.91%. Associating Cases II and Case III, the presence of an opening is synonymous to the manifestation of stress concentration at all points with the exception of Column ④. As the immediate area approaches Column ④, stress concentration decreases; and exactly at Column ④, reinforcement is performing its function of strengthening the part from 8.16% up to 12.44%. This analysis is pertinent when the door opening is on the compression side.

5. Conclusions

This study investigates the trends of stress concentration at a door opening of an offshore tubular steel tower. Three cases are modeled and are subjected to normal and abnormal design condition. The door opening is situated on the compression side, and out of twenty-seven points of interest observed, the characteristic and typical value of stress concentration is 1.45. Based on the results, circumferential or hoop stress plays the more crucial factor contrary to axial

stress. Utilization of reinforcement has decreased the principal stresses at all points of interest up from 13.13% up to 78.27%. In cases with reinforcement, the presence of an opening is synonymous to the manifestation of stress concentration at all points with the exception of points at middle column, and as the immediate area approaches Column 4, stress concentration decreases. Further studies could be made by conducting buckling and fatigue limit states. Moreover, experiments such as strain gage method, photoelasticity method, brittle coating technique or grid method can help verify the result of this study.

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