Sustainable Solutions in Structural Engineering and Construction
Edited by Chantawarangul, K., Suanpaga, W., Yazdani, S., Vimonsatit, V., and Singh, A.

ISBN: 978-0-9960437-0-0

DESIGN OF DOUBLE-SKINNED COMPOSITE TUBULAR OFFSHORE WIND TURBINE TOWERS

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A double-skinned composite tubular (DSCT) offshore wind power tower was proposed and automatic section design software was developed. The developed software adopted a nonlinear material and nonlinear column model. As long as the outer diameter, material properties, and requested capacities are known for the DSCT wind power tower, the developed software can perform axial force-bending moment-interaction analyses for hundreds of sections of the tower, as well as suggest ten optimized cross-sectional designs. Assuming that the inner and outer tubes were made of steel, the software performed experimental design processes for a 5.0 MW and a 3.6 MW turbine. The software suggested rational and satisfactory section designs, and showed the possibility of a DSCT tower being used as an offshore wind power tower.

Keywords: Wind power, Tower, Design, Optimum, DSCT, Composite.

1 INTRODUCTION

Due to high energy prices and supply uncertainties, many countries are trying to develop renewable energies such as wind power, tidal power, geothermal power, and photovoltaic power. Among them, wind power has been evaluated as having the best energy efficiency. Several offshore wind farms are planned and have been constructed around the world. According to the Global Wind Energy Council (GWEC), the installed wind turbines have produced up to 282,430 MW worldwide as of 2012. The world average annual growth rate of wind turbine installation from 1996 to 2012 was 27.7%, and the annual growth rate for 2012 was 18.7%. Due to the growth of offshore wind energy market, in 2009 the installation of wind turbines grew from 26,721 MW to 38,708 MW, or 44.8% (Sawyer 2013).

Offshore wind power emerged in the 1980s by focusing on the development of offshore wind farms. By 2008, offshore wind farms generated 25,413 TWh/year. Currently, the United Kingdom and several countries in Europe are leading the offshore wind farm construction and operation. Table 1 shows the installed capacities of offshore farms (Sawyer 2013). Table 2 shows the offshore wind farm development plan of South Korea (Sung 2012).

Because of better wind quality offshore than onshore, offshore wind farms are increasing in number, and the size of generating turbines, blades, and support structures is also increasing. However, as the support structure gets larger, its slenderness ratio increases, making the support structure more prone to buckling (Figure 1). Therefore, to reduce the possibility of buckling failure, a stronger tower structure is necessary.

Table 2. Offshore wind farm development plan of Korea (Sung 2012).

Plant	Capacity (MW)	Remark
Southwest Sea	2,500	Investigating wind condition
Jeonnam	4,000	Investigating wind condition
Sam-Mu	30	12.7 (under construction)
Daejeong	200	Design process
Han-Lim	150	Investigating wind condition
Haengwon	60	Design process
Total	6,940	

Table 1. Top 10 EU countries in offshore wind power (Sawyer 2013).

Country	Number of farms	Number of turbines	Capacity installed (MW)
UK	20	870	2,947.9
Denmark	12	416	921.0
Belgium	2	91	379.5
Germany	6	68	280.3
Netherlands	4	124	246.8
Sweden	6	75	163.7
Finland	2	9	26.3
Ireland	1	7	25.2
Norway	1	1	2.3
Portugal	1	1	2.0
Total	55	1,662	4,995

In this study, a double-skinned concrete-filled tube (DSCT) was adopted as the wind power tower to resolve the buckling problem. Automatic section-design software of a DSCT wind power tower was developed based on the nonlinear material model (Han et al. 2010) and nonlinear column model (Han et al. 2013), taking into consideration the confining effect of concrete. By using the developed software, a section design and performance analysis for the DSCT wind power tower was carried out. The designed DSCT tower was set to satisfy the required capacities to support 3.6 MW and 5.0 MW turbines, supported by the reference steel wind power towers.

Figure 1. Buckling failure of steel tower.

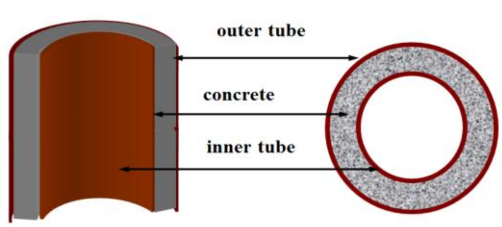

Figure 2. Cross section of DSCT column.

2 AUTOMATIC DESIGN PROGRAM FOR THE DSCT TOWER

2.1 DSCT column

A DSCT column was proposed by Shakir-Khalil and Illouli (1987), composed of two concentric tubes with concrete between them (Figure 2). After them, the axial strength of the DSCT column was studied (Wei et al. 1995, Zhao and Grzebieta 2002, Tao et al. 2004) and it was reported that the axial strength of a DSCT column was larger than the sum of axial strengths from the inner tube, outer tube, and concrete (Wei *ibid*). Recently, a hybrid column composed of FRP (fiber reinforced polymer) tubes and concrete has been studied (Teng et al. 2006, Yu et al. 2006). Han et al. (2010, 2013) proposed a material nonlinear and column model of a DSCT column, and studied the bending strength of a DSCT column.

In this study, an automatic section design program for a DSCT tower was coded in FORTRAN language, based on the nonlinear column model proposed by Han et al. (2013). The strain compatibility of the DSCT tower was derived from the section analysis, and the relation of curvature and lateral displacement was defined. In the nonlinear material model proposed by Han et al. (*ibid*), the confining stress was derived from the free body diagram (Figure 3). The failure of the inner tube depends on its buckling strength, yielding strength, and confining stress.

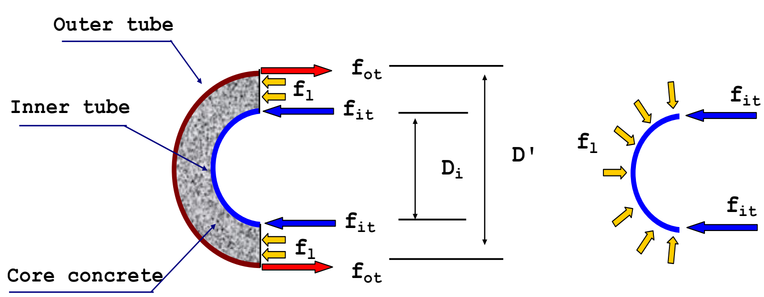

Figure 3. Confining stress on concrete in a DSCT column.

2.2 Automatic Design Program

The developed design program performed the section design of a DSCT tower in the procedure shown in Figure 4. The program performs P-M interaction and P-Δ analyses when given the input data on the outer diameter, the material properties, the required bending moment, and the axial strength of the tower. As a result, the program shows the optimum case, then designs cases that satisfy the required capacities.

The program internally calculates the minimum required thickness of the outer tube. After deciding the thickness of the outer tube, the hollow ratio is changed in ten steps from 50% to 95%. For every step, the thickness of the inner tube is calculated. A P-M interaction analysis was performed by increasing the thickness of the inner tube gradually by 0.01mm at every step. The DSCT tower was analyzed under the procedure shown in Figure 4, and recommended ten design cases satisfying the minimum requirements. The program determined the case with the smallest cross-sectional area as the most economical case. In step 5 of Figure 4, the nonlinear analysis model suggested by Han et al. (2013) was used.

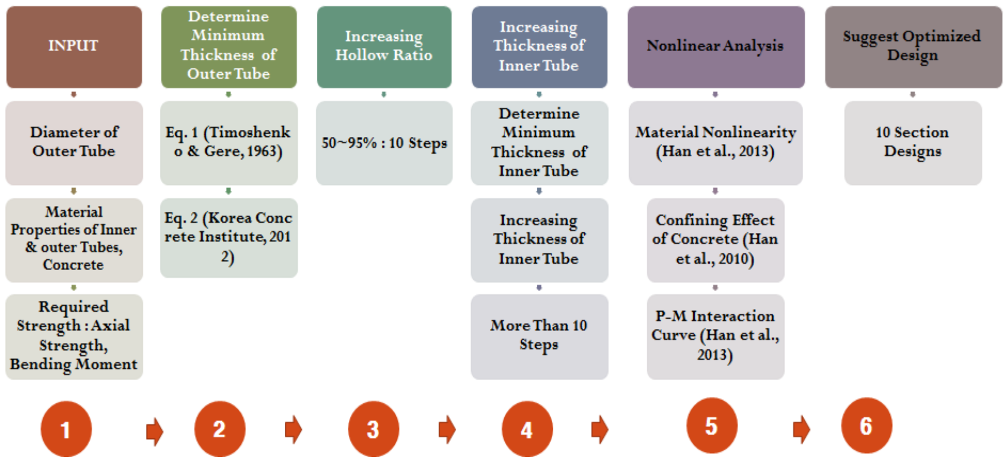

Figure 4. Design process in developed programs.

Table 3. Reference turbines.

Turbine size	Rotor diameter	Hub height	Nacelle mass incl. Rotor	Tower top diameter/wall thickness	Tower bottom diameter/wall thickness	Tower mass	Vertical load	Extreme load
3.6 MW	106m	72.5m	220tons	3.5m/15mm	4.5m/30mm	220tons	4.40 MN	7.10 MN
5 MW	126m	82.5m	410 tons	4.5m/20mm	6.0m/35mm	300tons	89.90 MN-m	150.00 MN-m

3 THE AUTOMATIC DESIGN OF A DSCR WIND POWER TOWER

In this study, the designs of the steel wind power towers applied in Kriegers Flak Offshore Wind Farm (Ljjj and Gravesen 2008) were referenced. Their dimensions and other information are summarized in Table 3. The designed DSCT towers had smaller diameters than the referred steel towers, with larger axial strengths and bending moments than the minimum requirements. DSCT towers with steel tubes were automatically designed for 3.6 MW and 5.0 MW turbines. Therefore, the minimum required axial load and bending moments were set as shown in Table 3. Three cases of DSCT towers with reduced diameters were designed for 3.6 MW and 5.0 MW turbines as shown in Table 4,. Table 5 shows the automatically-designed sections of DSCT wind power towers for 3.6 MW turbines. Figure 5 shows P-M interaction curves of the designed DSCT towers.

Table 4. Design model of DSCT tower with steel tubes.

Diameter Ratio*	3.6 MW Steel Tube DSCT Tower		5.0 MW Steel Tube DSCT Tower	
	Diameter	Model	Diameter	Model
0.7	3,150mm	3S7	4,200mm	5S7
0.5	2,250mm	3S5	3,000mm	5S5
0.4	1,800mm	3S4	2,400mm	5S4

Diameter Ratio*: Diameter of DSCT Wind Tower / Diameter of Steel Tube Wind Tower

Table 5. Recommended section design for 3.6 MW DSCT wind tower with steel tubes.

Design Case for 3S7	701	702	703	704	705	706	707	708	709	710
Outer Diameter (mm)	3,150	3,150	3,150	3,150	3,150	3,150	3,150	3,150	3,150	3,150
Diameter of Hollow Section (mm)	2,993	2,835	2,678	2,520	2,363	2,205	2,048	1,890	1,733	1,575
Hollowness Ratio (%)	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
Thickness of Outer Tube (mm)	12.50	11.00	10.00	8.50	8.00	7.00	6.50	6.00	5.50	0.50
Thickness of Inner Tube (mm)	13.15	11.69	10.53	9.13	8.31	7.25	6.49	5.76	5.05	4.38
Design Case for 3S5	501	502	503	504	505	506	507	508	509	510
Outer Diameter (mm)	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250
Diameter of Hollow Section (mm)	2,138	2,025	1,913	1,800	1,688	1,575	1,463	1,350	1,238	1,125
Hollowness Ratio (%)	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
Thickness of Outer Tube (mm)	26.00	26.00	25.50	25.00	25.00	24.50	24.50	24.50	24.00	24.00
Thickness of Inner Tube (mm)	27.17	25.74	23.84	22.00	20.63	18.87	17.52	16.17	14.52	13.20
Design Case for 3S4	401	402	403	404	405	406	407	408	409	410
Outer Diameter (mm)	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800
Diameter of Hollow Section (mm)	1,710	1,620	1,530	1,440	1,350	1,260	1,170	1,080	990	900
Hollowness Ratio (%)	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
Thickness of Outer Tube (mm)	41.00	42.00	42.50	43.00	44.00	44.50	45.00	45.50	46.00	46.50
Thickness of Inner Tube (mm)	42.85	41.58	39.74	37.84	36.30	34.27	32.18	30.03	27.83	25.58

4 CONCLUSION

The automatically-designed DSCT towers satisfied the required axial and bending strengths. They also showed superior performance to the referenced steel wind towers even though they had smaller diameters. According to this result, a DSCT column can be a good candidate for future offshore wind power towers, and the developed design software can give rational design sections. Therefore, it will be very useful to the engineers who design wind towers, piers, and building columns.

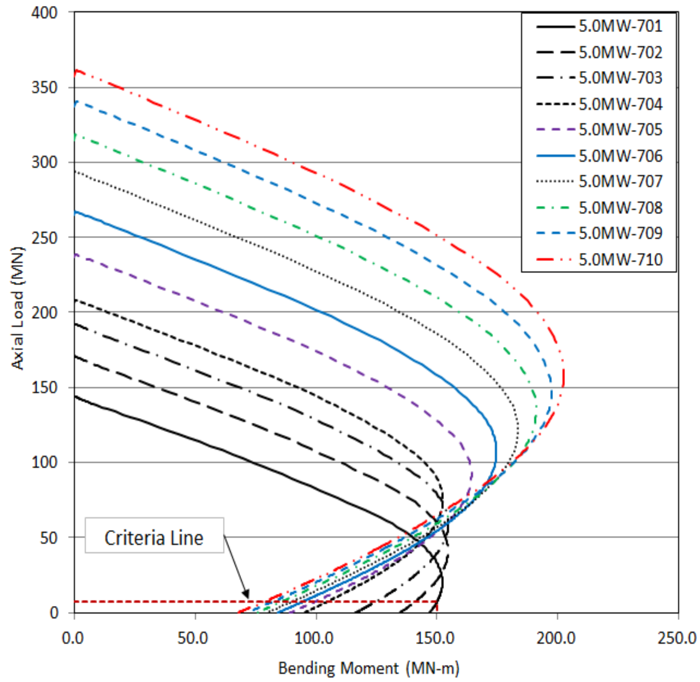

Figure 5. P-M interaction curves - design case for 5S7.

Acknowledgments

This research was financially supported by the Ministry of Land, Infrastructure and Transport (MOLIT) of the Korea government (code 12 Technology Innovation E09) and Korea Institute of Ocean Science and Technology (project no. PE99274).

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