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RESISTANCE OF DOOR OPENINGS IN TOWERS FOR WIND TURBINES

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Abstract. *In this paper, a study of resistance of a lower part of a wind tower including a door opening is presented. Nonlinear 3-D shell element models with real geometry of lower tower segment have been used to simulate the thin walled shell structure in order to study the influence of door opening on the strength of the tower. Two possible alternatives for strengthening the door openings were considered: (i) increasing thicknesses of plate around the opening and (ii) stiffening the opening by a stiffener. Buckling analysis and nonlinear analysis were performed to obtain critical buckling modes and strength of the tower segment. Nominal material properties of different steel grades were considered to investigate possibility of using higher strength steels. A parametric study considering possible local shell imperfections according to EN1993-1-6 has been considered. Additionally, comparative studies have been performed based on the FE model without door opening.*

1 INTRODUCTION

The basic components of a horizontal axis wind turbines (HAWT) are composed of a generator, a tower and foundation. Steel towers are manufactured and assembled from segments by welding or bolting. One important and indispensable part of tower is a door opening. It is used for operation and maintenance of wind turbines. However, this part affects significantly the strength of towers. In numerical simulation, steel tower of wind turbines have been considered as thin walled shell structure. Many deep researches of thin walled structures have been carried out [1, 2, 3]. Principles of design of thin walled structures can be found in EN1993-1-6 [4, 5]. Several researches have been performed to study behaviour of tower for wind turbines. Numerical analysis was carried out by D.L.Karabalis with real geometry of a wind turbine [6]. Stresses at door opening and buckling analysis were reported. Another experimental and numerical investigation of wind turbine tower under bending has been performed by Dimopoulos [7]. In this research, six specimens of down scaled models: two models without opening, two opening models without stiffening and two models with stiffener were tested. Comparisons of results from numerical and experimental study were presented. However, influences of varying thickness and stiffener of door opening on strength of the tower were not taken into account in any of these studies.

The principal purpose of this paper is to study in more detail the effect on the strength of steel tower of door opening and respective stiffening countermeasure like thickness increase or stiffeners. The parameters taken into account in this study correspond to real designs situation of steel wind turbine towers. Concerning the analysis methodologies, firstly, linear perturbation analysis of models have been performed in order to get elastic buckling modes and eigenvalues in 'perfect' geometry. Secondarily, nonlinear analysis of models with imperfection geometry from buckling mode has been considered. Comparative studies based on varying parameters and steel grade were also carried out and included in this paper.

2 FINITE ELEMENT MODEL

The lower segment of steel tower of real wind turbine structure was modelled using Abaqus. Three types of FE models of the cylindrical shell were considered: model without opening, models with door opening surrounded by thicker steel shell (models with varying thickness) and models with door opening surrounded by welded stiffener (models with stiffener). Geometries of the tower segment are as follows: 6666 mm of height and diameters of 4150 mm on the bottom and 3919 mm on the top. Thickness of wall of models is 37 mm. Thickness of door opening and stiffener range from 37 mm to 60 mm. Details of geometries are showed in Fig 1. Boundary conditions were determined according to EN1993-1-6 [5] and referred to case of open tank with anchors: BC3 (radially - W, meridionally - U and rotation - R_ϕ are free) and BC1f (radially - W and meridionally - U are restrained and rotation - R_ϕ is free) on the top and bottom of the structure respectively, (see Fig 2). External load was applied on the model through a reference point [8] coupled with the cross section on the top of model.

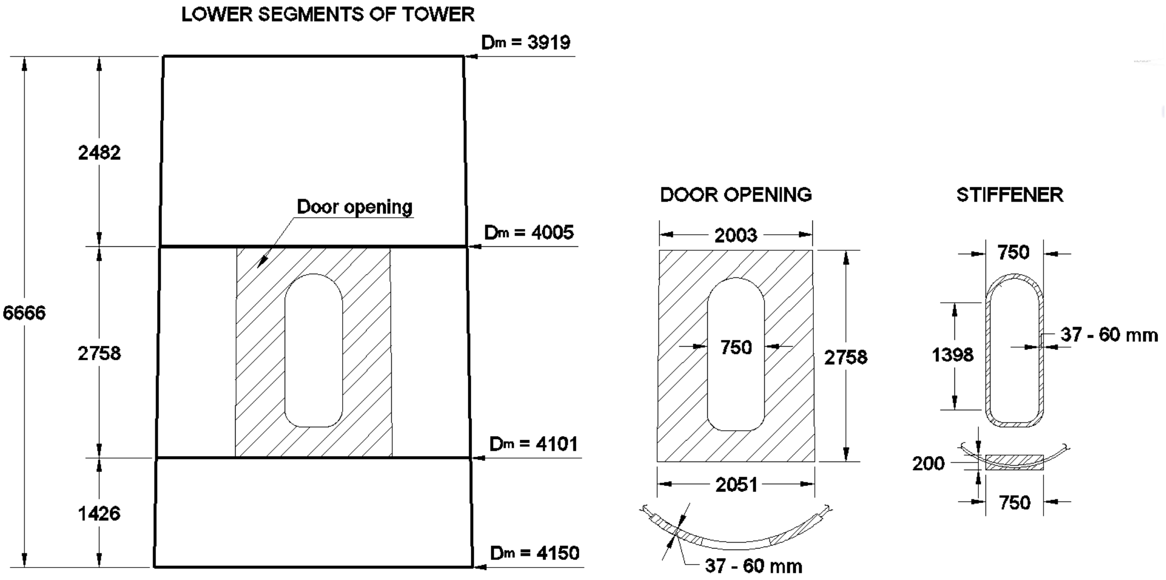

Figure 1: Geometry of Models.

The commercial finite element analysis program Abaqus [8] was used in the analyses of the models. In Abaqus, different types of shell elements are available for use: S3 (shell element with 3 nodes and full numerical integration), S4 (shell element with 4 nodes and full numerical integration), S4R (shell element with 4 nodes and reduced numerical integration), S8R (shell element with 8 nodes and reduced numerical integration). Shell element S4R is appropriate for large strain of buckling and riks analyses. Therefore, this type of shell element was used in this study. The quality and symmetry of mesh was especially considered in order to get more accurate results. The FE mesh was divided in two parts: the wall part and the door opening part including varying thickness or stiffener, (see Fig 2).

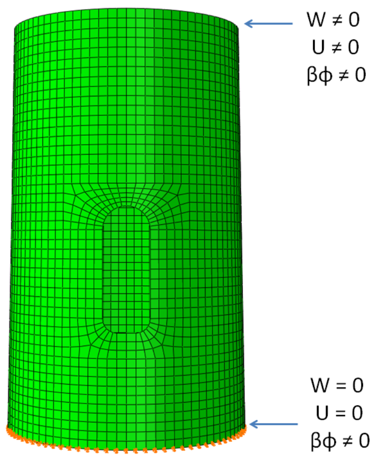

Figure 2: Boundary conditions.

3 MATERIAL CHARACTERISTICS

Steel S355 has been widely used to manufacture segments of steel towers for wind turbines. However, higher strength steels have been also studied and applied on manufacturing towers of wind turbines. In this study, S500 and S650 were also considered in order to investigate the possibility of using higher strength steel. In elastic domain, the Young's modulus of E=210 GPa and the Poissons ratio v=0.3 were used. In plastic domain, the engineering stress - strains relationship was converted into true stress - true plastic strains relationship using following equations:

$$\sigma_{true} = \sigma_{nom}(1 + \epsilon_{nom}) \tag{1}$$

$$\epsilon_{true} = ln(1 + \epsilon_{nom}) - \frac{\sigma_{true}}{E_0} \tag{2}$$

Fig 3 shows the curve of true stress and true plastic strain of Steels S355, S500 and S650 as input parameters to Abaqus.

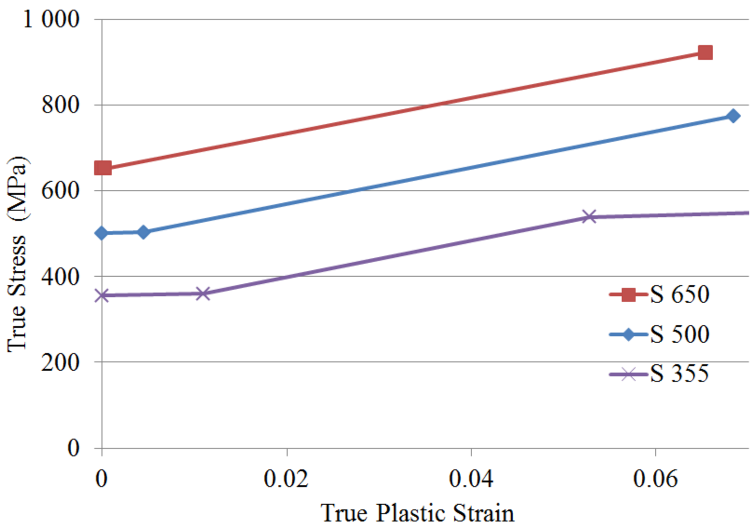

Figure 3: True stress and True strain curve of Steels.

4 NUMERICAL INVESTIGATION

4.1 Geometrical imperfection

Geometrical imperfection was used as input parameter to nonlinear analysis. This value influences the ultimate strength and deformation of the models. Equations to calculate the geometrical imperfection are recommended by EN1993-1-6[4] as follows:

$$\Delta w_k = \frac{1}{Q}\sqrt{\frac{r}{t}}t \tag{3}$$

where: t is thickness, r is radius and Q is the meridional compression fabrication quality parameter. This value depends on fabrication tolerance quality class and is given in Tab 1.

Fabrication quality parameter	Description	Q
Class A	Excellent	40
Class B	High	25
Class C	Normal	16

Table 1: Values of fabrication quality parameter Q.

4.2 Parametric study

A total of 35 FE models of lower segments of steel tower were analysed and compared in the parametric studies. Models with thickness of door openings or stiffener ranging from 37 mm to 60 mm were analysed. Thickness of tower wall was kept constant equal to 37 mm and the total height was kept at 6666 mm. In order to compare results, the model without door opening has the same height and 37 mm of wall thickness. All the models had the same diameters. In addition, characteristics of Steel S500 and S650 were considered for comparative analyses.

4.3 Geometrically and materially nonlinear imperfection analysis (GMNIA)

The sequence of buckling analyses consist of Linear analysis (LA), Geometrically nonlinear analysis (GNA), Geometrically and Materially nonlinear analysis (GMNA)and Geometrically and Materially nonlinear analyses with imperfection modes (GMNIA). These analyses depend on calculation level and slenderness parameters. The relations between these analyses are presented in Fig 4.

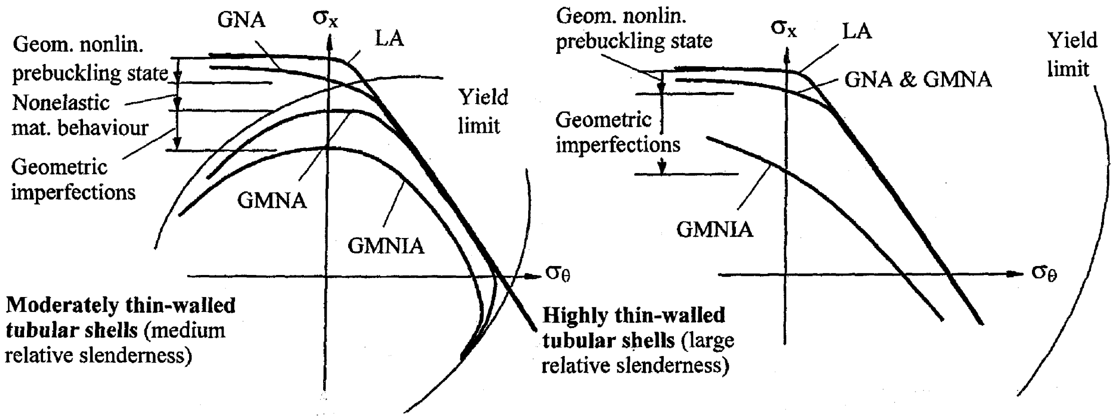

Figure 4: Sequence of analyses of buckling [9].

In the GMNIA analyses, buckling analysis is initially performed in order to get buckling modes. It should be noted that buckling analysis is carried out in linear elastic domain. Secondly, imperfection model of first buckling mode is considered. The basis of GMNIA analysis is the Risk method. This method was developed by Wempner (1971)[10], Riks (1972, 1979)[11, 12] and later supplemented by other several authors. In the Riks method, nonlinear static equilibrium solution is to produced for unstable phenomena. Load magnitude is treated as unknown value and modified until convergence reaches equilibrium path. The method is suitable for the analyses of thin walled structures. [13, 14].

5 RESULTS AND DISCUSSION

5.1 Buckling analysis

The most important in buckling analysis is the calculation of the eigenvalues and respective mode shapes of the structure. In Abaqus, the essential equation in buckling analysis is presented [8] as follows:

$$K^{MN} v^M = 0 \tag{4}$$

where: K^{MN} is the tangential stiffness matrix when loads are applied, v^M is nontrivial displacement solution. The critical buckling loads are defined as follows:

$$P^N + \lambda_i Q^N. \tag{5}$$

where: P^N is preload pattern, Q^N is perturbation load pattern, λ_i is eigenvalue.

Fig 5 presents the results of the first buckling mode of the models. Buckling mode shape of the model without door opening is characterized by local buckling waves. The magnitude of deformations decrease gradually from top to bottom of the model. In model with varying thickness and model with stiffener, buckling occurs at door opening with different deformations.

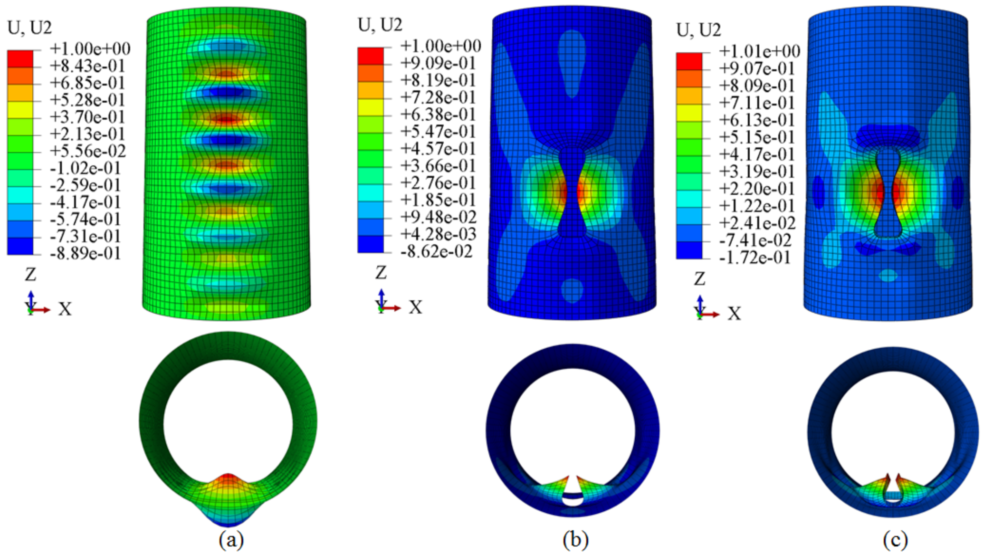

Figure 5: First buckling mode of the models: (a) Model without door opening, (b) Model of a door opening with varying thickness, (c) Model of a door opening with stiffener.

The eigenvalues presented in Table 2 increase gradually among modes of each model. It is interesting to emphasize that the first eigenvalue of model with varying thickness and of the model with stiffener decrease to 47.6 % and 69.8 % respectively in comparison with the model without door opening. Eigenvalues of model with varying thickness are smaller than model with stiffener (68.2 % of first mode and 74.2 % of third mode).

5.2 Nonlinear analysis

After performing the buckling analysis, geometrically and materially nonlinear analyses with imperfection modes (GMNIA) were carried out in order to predict ultimate strength of the structure. In Abaqus, the Riks analysis uses load multiplier as unknown value. The multiplier

	Model without door opening	Model of a door opening with varying thickness	Model of a door opening with stiffener
Mode 1	-1.000	0.476	0.698
Mode 2	1.000	0.487	0.712
Mode 3	1.002	0.580	0.782

Table 2: Comparison of eigenvalues between models.

is increased during the analysis until collapse of the structure. Magnitude of the proportional load is defined [8] as follows:

$$P_{total} = P_0 + \lambda(P_{ref} - P_0) \tag{6}$$

where: P_0 is the dead load, P_{ref} is reference load vector and λ is load proportionality factor.

Fig 6 shows moment-rotation curves of models with the same primary input parameters, in which, the half of tower with door opening is under compression. Thickness of both door opening and stiffener is 60 mm. These values are close to real for design of wind towers. The curves consist of two parts: the linear behaviour before buckling point and nonlinear behaviour in post-buckling. In first part, three curves are linear and almost coincident. In second part, the curves behave nonlinear up to ultimate strengths of 175.7 MNm, 193 MNm and 189.7 MNm corresponding respectively to model without door opening, model with varying thickness and model with stiffener respectively. In conclusion, values of ultimate strength show that both stiffening solutions are sufficient to strengthen the structure. However the big differences in the ultimate strengths justify further studies to optimize stiffening solutions.

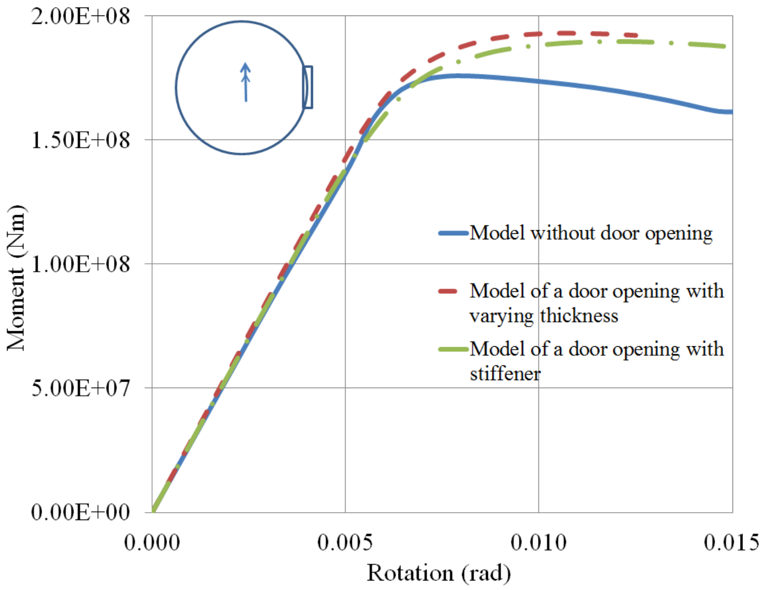

Figure 6: Relation between moment and rotation of models - door opening under compression.

Fig 7 presents moment-rotation relationship of models which have the half of tower with door opening under tension. Ultimate strength of model with varying thickness and model with stiffener are 194.9 MNm and 192.0 MNm, respectively. In comparison with models that have a half of tower with door opening under compression, the difference is just 1%. It may lead to conclusion that the position of a door opening (under compression or tension) does not affect the ultimate strength of towers with the same conditions.

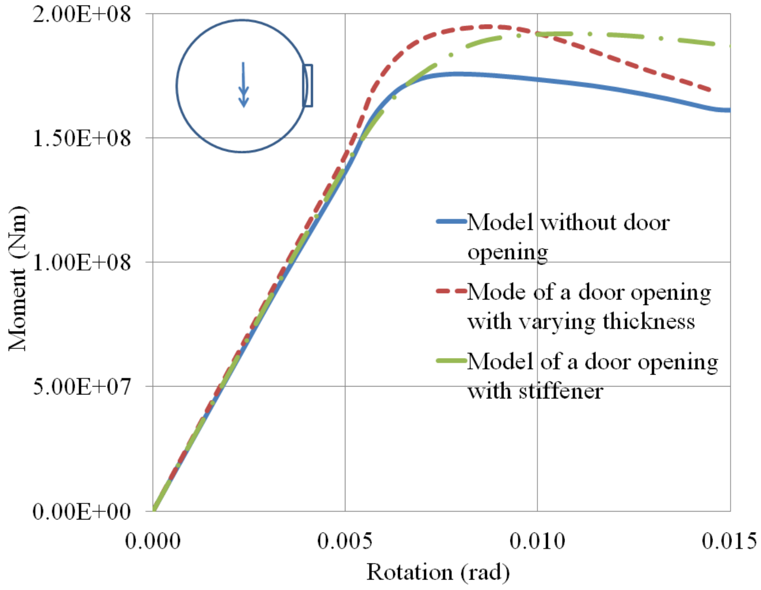

Figure 7: Relation between moment and rotation of models - door opening under tension.

Fig 8 presents the distribution of normal stresses at ultimate load in all models. Distribution of normal stresses in the model with varying thickness shows big difference between wall area and door opening area. Stress concentration occurs around door opening. Normal stresses in tension and compression in the model with varying thickness are 382.4 MPa and -457.0 MPa respectively. As mentioned above, the ultimate load of model without door opening is lowest (175.7 MNm). However, its normal stress in tension is the highest (412.6 MPa). Besides, that normal stress in compression of model with stiffener is minimum (-495.8 MPa). It should to be noted that Steel S355 was used in analyses of these models. It proves that yield phenomenon appeared in parts of the models.

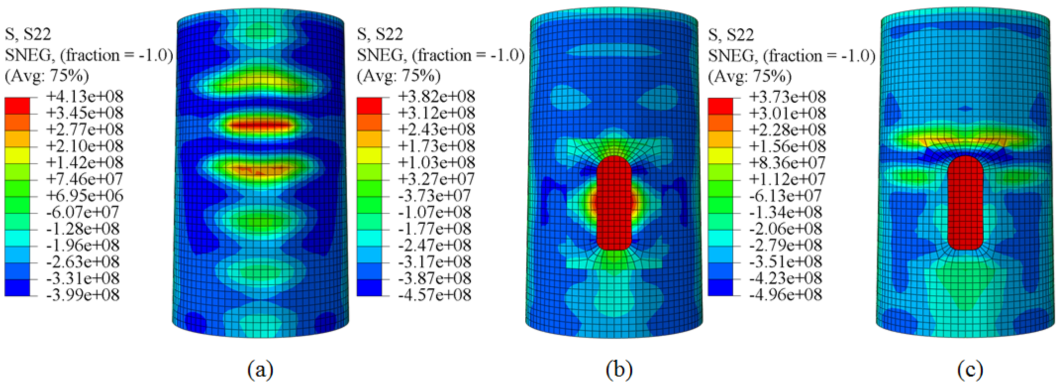

Figure 8: Distribution of normal stress at ultimate load: (a) Model without door opening, (b) Model of a door opening with varying thickness, (c) Model of a door opening with stiffener.

Fig 9 shows distribution of reaction forces of the models for 0.0002 rad rotation applied on the top of the top of the models. The three curves almost coincide. They are typical shapes of distribution of reaction forces in linear part. It is interesting to emphasize effects of door opening on distribution of reaction forces. Outside the area of door opening, the curves of reaction forces are smooth. The results also show that distribution of reaction forces of models are approximate in pre-buckling part.

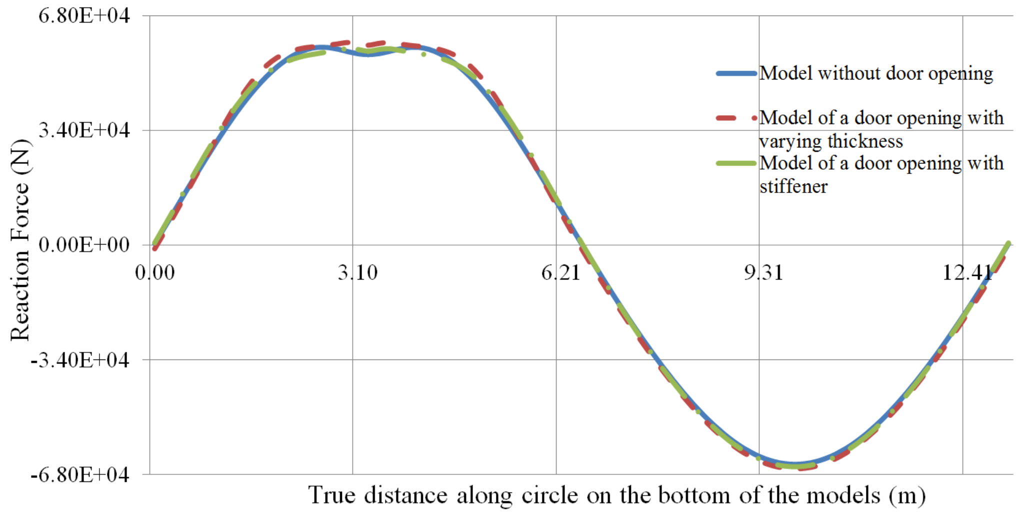

Figure 9: Distribution of reaction forces of the models at 0.0002 rad of rotation.

Fig 10 shows distribution of reaction forces of the models corresponding to 0.013 rad rotation applied on the top of the models. It should be noted that the figure presents distribution of reaction forces in nonlinear part. The curves of model with varying thickness and model with stiffener are almost coincident. Influence of buckling on distribution of reaction forces are significant. Minimum reaction forces at door opening area of the model with varying thickness and the model with stiffener are 921.6 kN and 895.1 kN respectively. However, at the same position, reaction force of model without opening is only 242.2 kN.

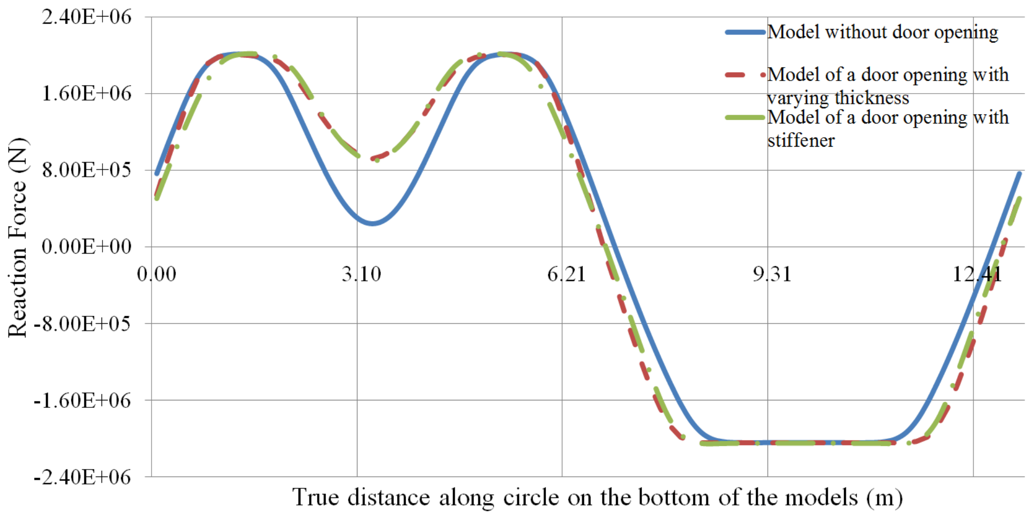

Figure 10: Distribution of reaction forces of the models at 0.013 rad of rotation.

5.3 Optimal designs of door opening and stiffener

In this study, varying thickness around door opening and of stiffener were considered. These results were analysed and compared with the results of model without opening in order to optimize the thickness of door opening and stiffener as well. The thickness range from 37 mm to 60 mm. These values are appropriate to design the stiffening of door opening. Table 3 presents results of relations between thickness, moment and rotation at ultimate load of the models. As mentioned above, the ultimate moment of model without opening is 175.7 MNm. In comparative studies of the door opening with varying thickness and of the door opening with stiffener, 51 mm of thickness of door opening and 37 mm of stiffener are sufficient to strengthen the structures.

	Door opening		Stiffener	
Thickness (mm)	Moment (MNm)	Rotation (rad)	Moment (MNm)	Rotation (rad)
37	163.910	0.01464	182.203	0.01357
39	163.092	0.01869	182.920	0.01357
41	163.531	0.01186	183.772	0.01088
43	165.130	0.01186	184.107	0.01357
45	167.618	0.01015	184.668	0.01357
47	170.473	0.01015	185.252	0.01357
49	173.347	0.01015	185.864	0.01357
51	176.392	0.01015	186.631	0.01186
53	179.654	0.01015	187.703	0.01186
55	183.084	0.01015	188.555	0.01186
57	187.160	0.01037	189.078	0.01186
59	190.870	0.01079	189.520	0.01186
60	192.976	0.01058	189.719	0.01186

Table 3: Relation between thickness, moment and rotation at ultimate load of the models.

5.4 Use of higher strength steels

In practice, design of wind towers is based on Steel S355. In this research, higher strength steels S500 and S650 were used for door opening and stiffener in order to study decrease of thickness without affecting the strength of towers.

Fig 11 presents moment-rotation curves of the tower when steel S355, S500 and S650 were used for the stiffener. The curves are similar in shape. Ultimate load is approximately 182 MNm. However, the thickness of stiffener significantly decreased as higher strength steels were used. It should be noted that in case of steel S355, the thickness of stiffener is 37 mm. When S500 and S650 are used, the thickness of stiffener decreases to 29 mm and 23 mm respectively. These correspond to approximate to 78% and 62% of the thickness of stiffener when steel S355 is used.

Fig 12 shows curves of moment versus rotation of the tower as Steel S355, S500 and S650 were used for the door opening. The shape of curves changed significantly as higher strength steels were used. Ultimate load is approximately 177 MNm. However, difference between pre-buckling and post-buckling is detected. The thickness of door opening significantly decreased

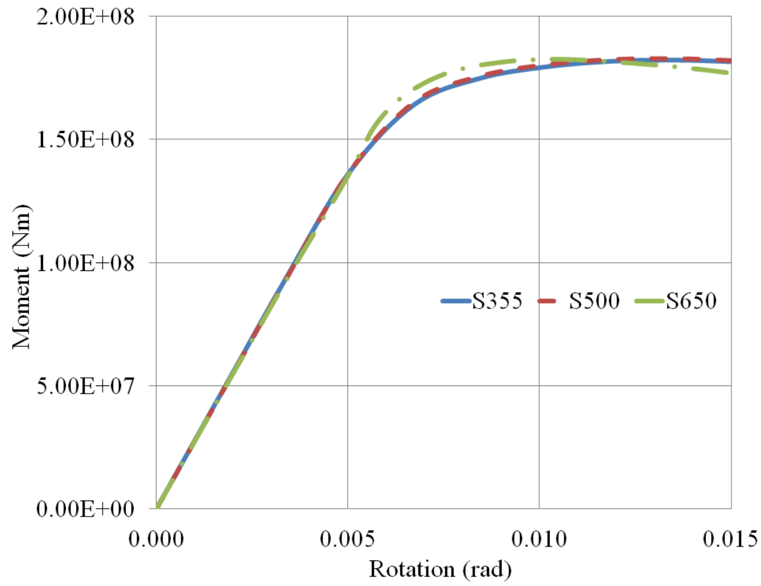

Figure 11: Comparison of using higher grade steels for stiffener.

as higher strength steels were used. It decreased to 41 mm and 35 mm for steel grades S500 and S650 respectively. It decreased approximately 20% and 33% in comparison to the thickness of door opening (51 mm) when steel S355 was used.

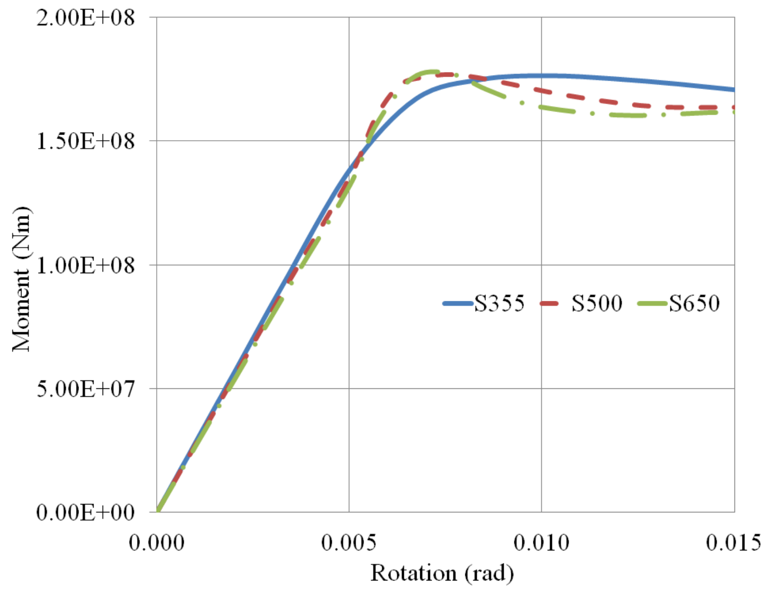

Figure 12: Comparison of using higher grade steels for door opening.

6 CONCLUSION

In this paper, the influence of door opening and respective stiffening were investigated. Comparative studies between model without opening, models with door opening surrounded by thicker steel shell and models with door opening surrounded by welded stiffener were presented. Linear and nonlinear moment-rotation behaviours of the thin walled structures were analysed. Results from comparative studies in cases of door opening under compression and tension showed that the position of door opening did not affect significantly the ultimate strength of tower (1% of difference) in the same conditions. Parametric study aiming at optimal designs of door opening and stiffener showed that 37 mm of stiffener and 51 mm of thickness around door opening are sufficient to obtain the same resistance in comparison with the model without door opening and 37 mm of wall thickness. In addition, results from studies when higher strength steels are used, have shown that thickness of door opening and stiffener decreased significantly when higher strength steels are used. Thickness of door opening just equalled approximately 80% and 67% of its value as steel S355 was used. Thickness of stiffener decreased by 22% and 38% as steel S500 and S650 were used for stiffener respectively.

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