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SANDWICH METAL FOAM RINGS FOR WIND TURBINE TOWER BUCKLING ENHANCMENT

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Abstract. *In this paper, a buckling analysis of wind energy towers is performed. Stiffening rings are used in various heights to enhance the dynamic behaviour of wind energy structures, making the tower stiffer and reducing the susceptibility of the structure to local buckling under external loads. The augmenting stiffening rings may be steel solid or composite, the latter being a sandwich steel ring filled with metal foam, either vertical or horizontal sandwich rings. This design approach aims to take advantage of low density of metal to achieve stiffening with a reduced bill of materials, whilst the porosity of the foam presents additional opportunities to control structural damping. Three different design configurations are considered to assess the buckling characteristics of the proposed approach: one unstiffened tower, one stiffened tower through solid steel rings, a stiffened tower with horizontal sandwich metal foam ring and a stiffened tower with vertical sandwich metal foam rings. Both linear and nonlinear buckling resistance were studied to evaluate the influence of sandwich rings. All stiffening schemes were compared in term of buckling improvement and mass increase, whereas the impact on the structure's modal properties is assessed*.

1 INTRODUCTION

Decarbonization of energy is one of the major societal challenges nowadays. Climate change gradually leaves its footprint due to high levels of CO2 and other hazardous emissions. Energy is primary produced by fossil fuels releasing high amounts of CO2. According to HM Government, gas is the primary fuel for electricity production, accounting for the 38.2% of the total energy [1]. Thus, the greenhouse effect is exacerbated and global warming getting more and more noticeable, not least through severe natural hazards that are related to climate change.

Wind energy is the most acceptable and efficient amongst renewables. Wind is a pure and inexhaustible source of energy, substituting corresponding energy generated by fossil fuels. In the United Kingdom, wind power was the dominant source of renewable energy since it covered 27% of the total energy demand for 2020 [2] . Wind energy is carried out by wind turbines. Wind turbine consists of the rotor hub, rotor blades, the nacelle and the blades. This system is supported by womd turbine towers (WTs). Installing WTs at ever increasing heights is therefore an area for continuous improvements and structural innovations. However, it is obvious that the constructional cost increases in proportion to the tower's height. The tower plays an important role in the overall constructional cost, since the Levelized Cost of Energy (LCOE) and the competitiveness of the harnessed energy is affected by the structural cost. Hence, a design combining increased height and a lesser cost of the tower would lead to more competitive LCOE.

WTs are complex systems that should operate under severe environmental conditions and thus wind turbine tower should provide structural integrity to ensure continuity and unproblematic energy output, during their lifetime. Wind towers are principally subjected to gravitational and dynamic forces. The self-weight of the tower, the weight of the nacelle and the rotor are considered as the main static loads of the structure. Dynamic external forces are much more important since they excite the vibrations of the whole system. The common dynamic loads that an onshore tower is subjected to during its lifetime are the vibrations of the rotating blades at the top of the tower, the wind pressure and more rarely earthquakes. In the case of offshore wind turbine towers, the tower will be subjected to wave and current loads as well [3]. Steel tubular tower is the most common design configuration. In general, it consists of cylindrical or conical sections of 20-30 m, which are transported and mounted on site. They benefit from their high capacity compared with their thickness, saving material cost. Furthermore, they are simple cantilever beams, and thus, simple calculations are needed for their design [4]. Nevertheless, there are some limitations in regards to the maximum diameter and thickness, since they should not exceed 4.5m and 75 mm respectively.

A higher tower is more flexible and thus it is more sensitive to dynamic loads. Therefore, increased energy output requires more productive systems via higher nacelle heights combined with reduced costs and resilience to dynamic excitations. Moreover, wind towers are usually constructed by thin-walled cylindrical tubular cross-sections, and thus, they are susceptible to local and overall buckling. Also, cylindrical shells are sensitive due to geometrical imperfections as well. Introducing ring stiffeners could be a trustworthy solution to overcome these questions. Ring stiffeners rings are added to the inner face of the tubular tower, increasing the stiffness and the bearing capacity of the tower. Mainly, they are used to enhance the tower against out of plane deformations [5]. Lavassas et al. studied a prototype wind turbine tower, simulating in detail the flanges and the stiffener rings [6]. Stavridou et. investigated the effect of stiffener rings in terms of linear and nonlinear buckling with imperfections, concluding that stiffener rings enhance the structural performance of the shell [7]. However, solid rings may increase the overall mass of the system and thus, the overall constructional cost.

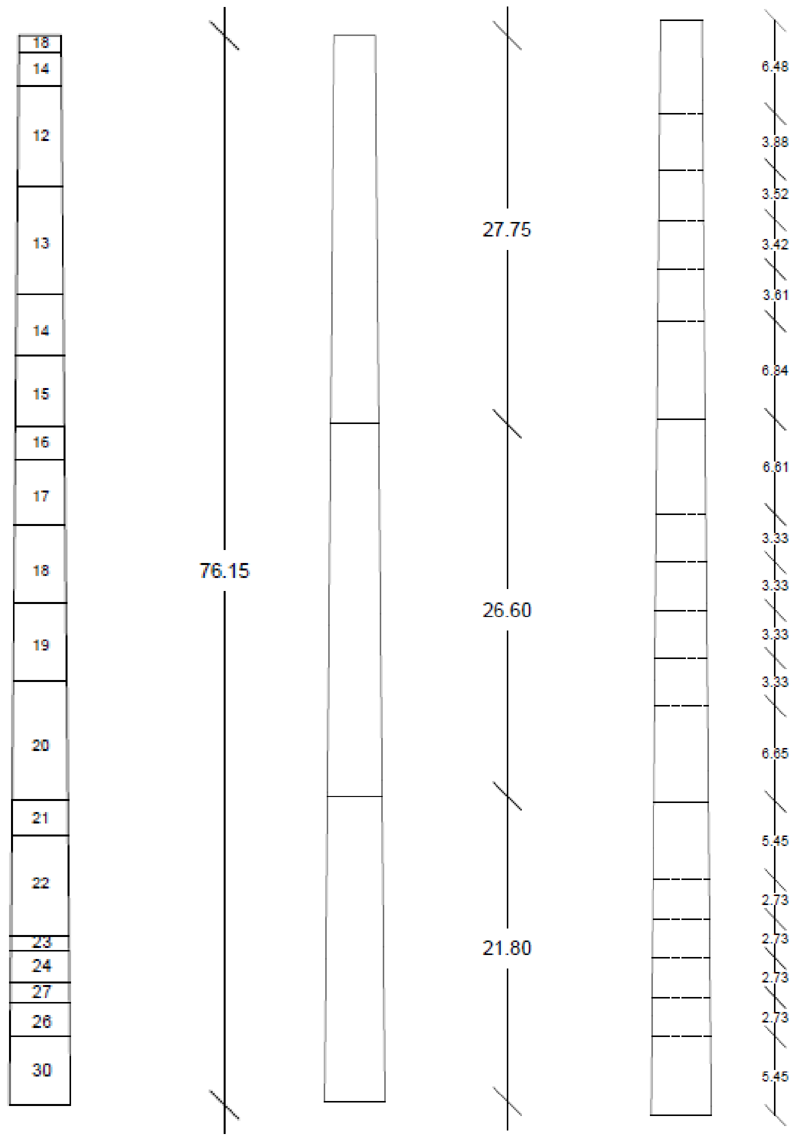
Therefore, alternative design configurations of ring stiffeners should be considered. Metal foam composite rings could be a promising method to tackle the above issues due to their low density, buckling resistance and energy absorption properties Metal foams are a new class of materials representing low density and novel physical and mechanical properties. They enjoy many mechanical characteristics of metallic materials such as excellent stiffness to weight ratio and high levels of plasticity. In addition, metal foams could be used as sandwich cores due to high shear strength, mechanical damper since the damping capacity is larger compared with solid metals and vibration controllers because having higher flexural vibrations[8].

To the authors' knowledge, sandwich metal foam rings have not been investigated for wind turbine towers. To bridge the gap, this paper examines the effectiveness of sandwich metal foam rings against buckling. A comparative study, in terms of linear and nonlinear buckling, is carried out examining four different tower configurations; an unstiffened, a solid-ring stiffened, a horizontal and a vertical sandwich ring stiffened tower. A modal analysis was carried to evaluate the dynamic properties of the towers. In addition, all the towers will be analyzed for linear buckling. The first eigenmode mode will be used to perform the nonlinear buckling. Afterwards, a comparison between the stiffening configurations were studied by means of structural improvement and overall mass increase.

2 NUMERICAL ANALYSIS

2.1 Model description

For the purposes of this paper, the wind turbine towers that have been already examined in the HISTWIN project will be considered [9]. The tower height is 76.15m and it has been divided into three parts to be transported on site. Their lengths are equal to 21.8 m, 26.6 m and 27.8m respectively (Figure 1). The parts are connected to each other through ring flanges. The tower has a conical shape where the bottom diameter is equal to 4.3m and the top diameter equal to 2.95 m. The thickness changes with the height, where it is 30mm at the bottom and 12 mm at the top. The ring flanges thickness are 60 mm om each part, meaning 120mm overall, and their width equal to 160 mm. Respectively, the ring stiffeners provide the same width with the flanges, differing in terms of their thickness, which is equal to 22 mm. Finally, the tower is embedded to a stiff concrete foundation and thus a fully fixed base is assumed.



(a) (b) (c)

Figure 1. Thickness (a), flange (b) and ring distribution(c) along the height

2.2 Loads

In this paper, the wind turbine tower is subjected to its self-weight, the loads produced by the wind turbine at the top and the wind pressure along the height of the tower. The self-weight is directly calculated through the finite element software ABAQUS, assigning steel's density (7850 kg/m^3) [10]. The rotor-nacelle assembly loads are provided by the manufacturer. These loads are a horizontal (H=600 kN), a moment load (M=48000 kNm) due to blades' rotational movement, and a vertical load due to overall weight of the turbine (V=1080 kN). The center of the mass of the turbine is located eccentrically from the horizontal (+ 0.725 m) and the vertical direction (+ 0.50 m).

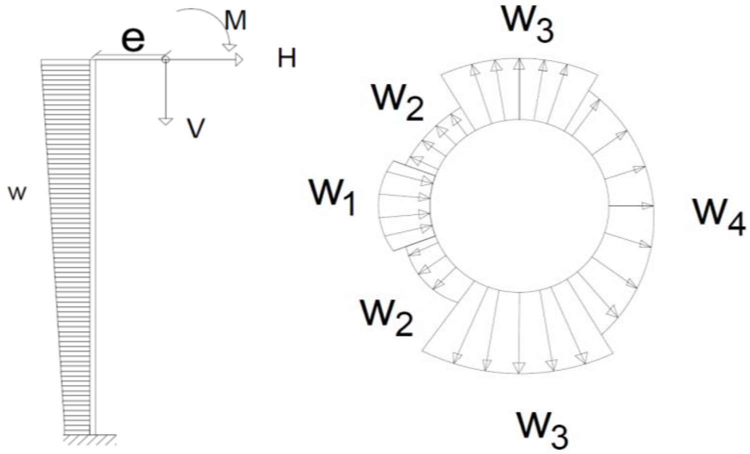


Figure 2. Wind loads along the height and the circumference of the tower

The wind load acting at the towers is calculated analytically following the Eurocode desing guidelines [11]. The fundamental wind velocity, for 10 m above the ground, was assumed equal to v_b =27 m/sec. The wind load didtribution is propotial to the tower's diamater, along its height. For a time period T=50 years, the force distribution F_w, given in kN/m can be estimated according to the follow equations:

$$z \leq 2\,m: \; F_w = 0.51 * D$$
$$z \geq 2\,m: \; F_w = 0.013 * \ln(20 * z) * [\ln(20 * z) + 7] * D \quad (1)$$

where D= -0.01775*z + 4,30266.

Respectively, the wind pressure is:

$$z \leq 2\,m: \; p_w = 0.51 * D/[\theta * \left(\frac{D}{2}\right)]$$
$$z \geq 2\,m: \; p_w = 0.013 * \ln(20 * z) * [\ln(20 * z) + 7] * D/[\theta * \left(\frac{D}{2}\right)] \quad (2)$$

Furthemore, the wind pressure in not uniformly didtributed around the circumference. According to Eurocode guidilnes [11], the external pressure coefficient Cp,o without free-end flow and the end-effect factor φλa have to been taken into account:

$$w = C_{p,o} * \varphi_{\lambda\alpha} * p_w \quad (3)$$

Deriving the circumference by 30 degrees and considering equations (3), (4), and (5), the wind pressure is given be the below expression:

$$w = \begin{cases} w_1 = 1.00pw & [0\text{-}30^o] \\ w_2 = 0.60pw & [30^o\text{-}60^o] \\ w_3 = 1.85pw & [60^o\text{-}120^o] \\ w_4 = 0.70pw & [120^o\text{-}180^o] \end{cases} \quad (3)$$

2.3 Model Analysis

The tower and designed and studied at the FEM Software Abaqus [10]. Both tower, flanges and ring stiffeners were modelled by S4R shell elements. These elements contain 4 nodes, each of them 2 displacement and 1 rotational degrees of freedom. For conventional shell elements, the geometry is defined by a reference surface and the thickness is indicated by section properties definition. Using this element configuration, stress distribution and thus, buckling can be easily observed. Ring stiffeners and flanges are connected via tie constraints with the main tower.

When it comes to the material properties, S355 is used. The material properties assigned in ABAQUS are: Modulus of Elasticity E=210 GPa, Poisson ratio's ν=0.3, Yield Stress 355 MPa and Ultimate Stress 510 MPa, Yield Strain 0.011 and Ultimate Strain 0.0528. Metal foam properties were defined by Yiatros et al. experiments [12] [13]. These properties are: Modulus of elasticity E=560 MPa, Poison ratio ν=0.05, Yield stress 5.68 MPa, yield strain 0.018 and ultimate strain 0.1. Metal foams are taking advantage of the extended plateau area and their low density 596 kg/m^3.

2.4 Stiffening configurations

For the purposes of this paper, an unstiffened tower will be compared with ring stiffened tower to assess the effectiveness of different ring-stiffening schemes. The different stiffening schemes that will be compared are:

- an unstiffened tower (Model_1),
- a 15-solid rings stiffened tower (Model_2),
- a 15-horizontally sandwich metal foam ring stiffened tower (Model_3) and
- a 15-vertically sandwich metal foam ring stiffened tower (Model_4)

The dimensions of the ring stiffeners have already been described in section 2.1. A schematic view of the horizontally and vertically sandwich rings is shown at Figure 3. Metal foam thickness is equal to 60 mm out of total 160 mm and 22mm height for the first case, whereas for the latter case, the metal foam consists of the 1/3 of the whole ring (7.33 mm high) and 160 mm thick.

2.5 Analysis methods

First of all, an eigenfrequency analysis is carried out to compute the eigenfrequencies and the mode shapes of the towers. In addition, since cylindrical shells, such as tubular wind turbine towers, suffer from buckling and therefore, both linear and nonlinear buckling analysis are performed. Through an initial linear buckling analysis, the theoretical buckling resistance load will be defined. The buckling shapes of this initial step will be used to carry out a the static geometrical and material nonlinear analysis with (GMNIA) and without imperfections (GMNA).

3 RESULTS

3.1 Modal analysis

The dynamic characteristics of both wind turbine tower models are defined by means of eigenfrequencies and mode shapes. The overall mass of the wind turbine tower, including the blades, the rotor and the nacelle, was assigned as a point mass at the top of the tower. The tower base was assumed to be fully fixed, without considering the soil-structure interaction. The results are presented in Table 1. All tower presents similar dynamic behaviour in terms of eigenfrequencies, which indicates that the herein design of the stiffening rings conforms to vibrational requirements for the tower. Likewise, for both models, the considered mode shapes are bending modes. The mode shapes for all the models are shown in Figure 4

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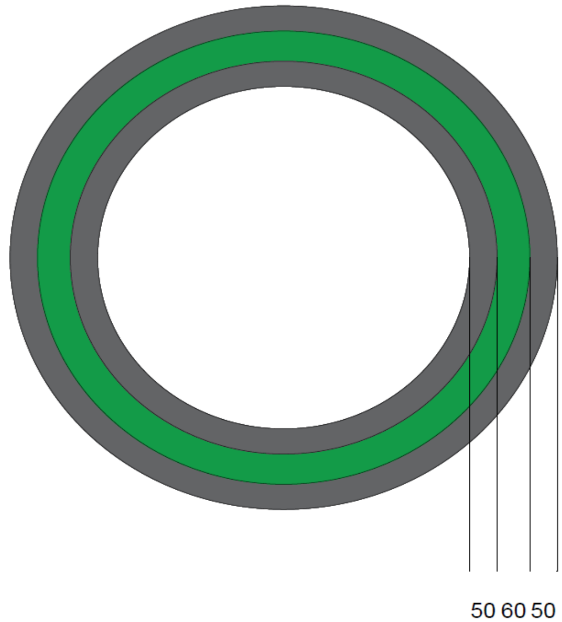

(a)

(b)

Figure 3. (a) Horizontal (top view) and (b) vertical sandwich ring (side view).

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	Model_1	Model_2	Model_3	Model_4
1st Mode	0.372	0.371	0.372	0.371
2nd Mode	3.085	3.029	3.058	3.086
3rd Model	8.577	8.427	8.506	8.539

Table 1. Eigenfrequencies of the tower

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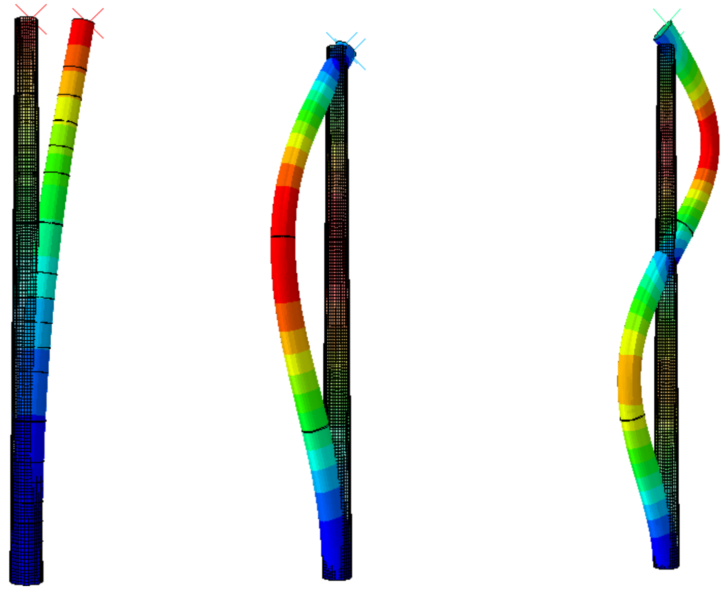

(a) (b) (c)

Figure 4. Mode shapes for both unstiffened and stiffened models, (a) First, (b) Second and (c) Third mode shape

3.1 Linear buckling analysis

An initial elastic buckling analysis is carried out in order to calculate the theoretical ultimate buckling load, assuming a perfect elastic tower. The deformed shape of the fundamental mode will be considered for the nonlinear analysis. Furthermore, linear buckling analysis indicates where local buckling will take place. In regards to the studied models, as it is shown in Figure 5, buckling occurs at the third part of the tower. It is obvious that the buckling area significantly decreases with the presence of stiffener rings. The influence of the stiffener rings is reflected in Table 2 as well, which shows the 3 first buckling eigenvalues of the models, which represent a comparative measure of the theoretical buckling load All stiffening configurations seems to increase significantly the buckling load. Model 2 seems to be the most effective stiffening configuration, with 29,4% increase of the buckling load. Amongst the two different sandwich rings configurations, the vertical one seems to be more beneficial yielding an increase of 16.4%. This analysis demonstrates that the composite metal foam rings can sufficiently increase the structure's resistance against buckling, however, a nonlinear analysis would be more accurate in estimating the effect of the considered configurations.

	Model_1	Model_2	Model_3	Model_4
1st	1.813	2.346	2.016	2.111
2nd	1.827	2.450	2.113	2.243
3rd	2.035	2.654	2.307	2.423

Table 2. Linear buckling results. Theoretical buckling resistance load.

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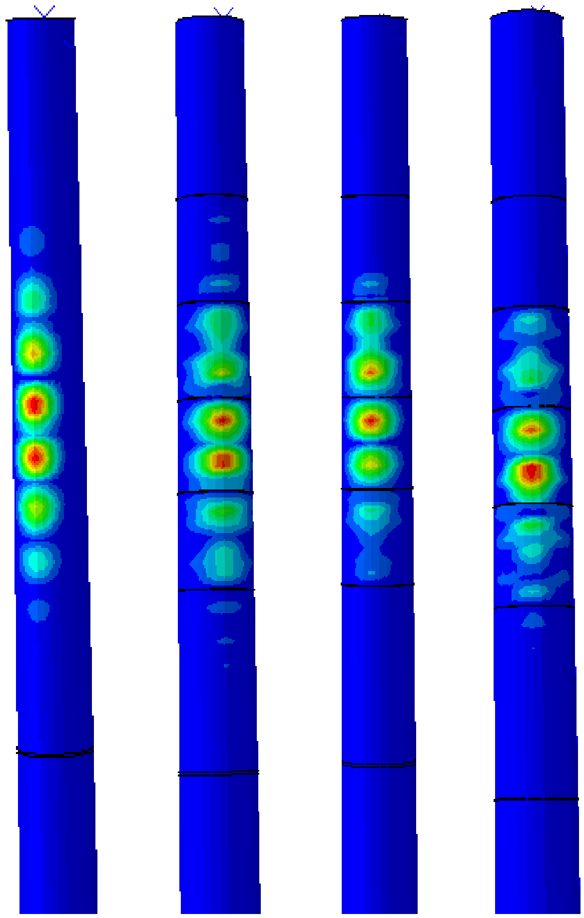

Figure 5. Fundamental buckling mode shapes for Model_1, Model_2, Model_3 and Model_4.

3.2 Nonlinear buckling analysis

Buckling occurs when Von Misses stresses overcome the steel yielding stress, which for the considered tower is equal to 355MPa. Results are presented in Table 3 and Figure 6. The responses of the models are presented in Figure 6, in which the vertical axis shows the levelized overall load and the horizontal axis the top displacement. Similarly, Table 3 represents the value of the ultimate buckling load, combined with mass of each model. This ultimate load expresses the level of the force until yielding occurs. The existence of the ring stiffeners remarkably improves the buckling resistance of the tower for both GMNA and GMNIA. However, imperfections reduce significantly the response, especially for the Model_1, in which the buckling load decresed about 13%. All stiffening configurations enhance the buckling behavior of the tower and Model 2 is the most effective stiffening configuration. Also, similarly with linear analysis, the vertical sandwich ring (Model_4) is more effective than the horizontall one (Model_2). Besides, Model_4 combines buckling resistance improvement with less additional mass, since vertical ring stiffeners add only 1.33 tn, instead of 5.97 tn of Model_2.

	Model_1	Model_2	Model_3	Model_4
GMNA	0.58P	0.66P	0.62P	0.64P
GMNIA	0.45P	0.55P	0.52P	0.54P
Mass (tn)	243.69	249.66	246.81	245.02

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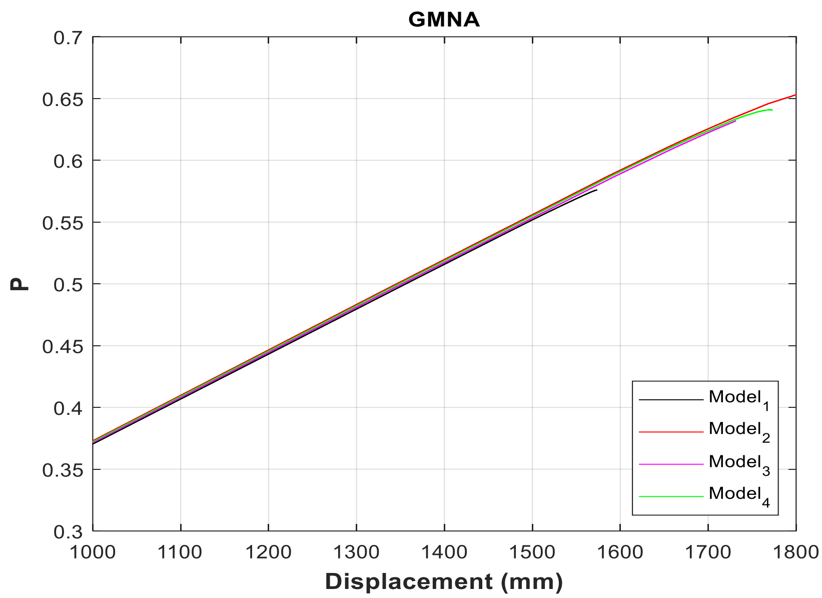
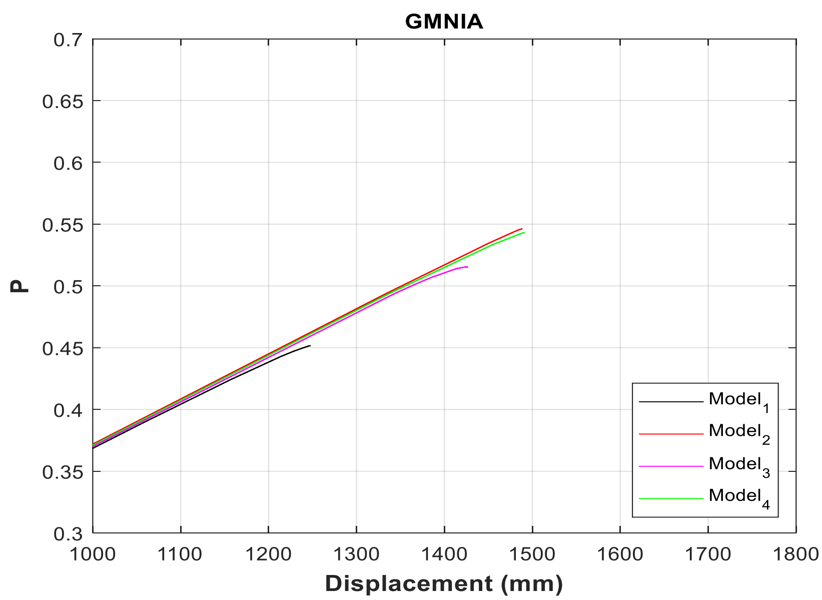
Table 3. GMNA and GMNIA results considering the additional mass of stiffening schemes



(a)



(b)

Figure 6. Ultimate buckling load level versus top displacement for both GMNA (a) and GMNIA (b)

4 CONCLUSIONS

Three different ring-stiffening configurations were studied in this paper, solid steel rings, horizontal and vertical sandiwch rings. All these different stiffening types were effective against linear and linear buckling. The linear buckling indicates the most sensitive area of the tower, where buckling occurs. Stiffener rings limit the buckling length and thus, reduce the tower sensitivity. In regards to the nonlinear buckling resistance, stiffener rings strenghten the tower as well. The presence of the imperfections results in 14% and approximatelly 10% reduction of the response of unstiffened and stiffened tower respectively. Finally, Model_2 and Model_4 presents similar results in terms of buckling resistance, however, Model_4, due to the existance of low density metal foam, does not increase signifacntly the overall mass of the structure.

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REFERENCES

1. Department for Business Energy and Industrial Strategy Energy Trends, UK, January to March 2021. **2021**.
2. WindEurope Wind energy in Europe, 2020 Statistics and the outlook for 2021-2025. **2021**.
3. Hernandez-Estrada, E.; Lastres-Danguillecourt, O.; Robles-Ocampo, J.B.; Lopez-Lopez, A.; Sevilla-Camacho, P.Y.; Perez-Sariñana, B.Y.; Dorrego-Portela, J.R. Considerations for the structural analysis and design of wind turbine towers: A review. *Renew. Sustain. Energy Rev.* **2021**, *137*, doi:10.1016/j.rser.2020.110447.
4. Baniotopoulos, C.C.; Lavassas, I.; Nikolaidis., G.; Zervas, P. Topics on the design of tubular steel wind turbine towers. In *Environmental Wind Engineering and Design of Wind Energy Structures. CISM Courses and Lectures*; Baniotopoulos, C.C., Borri, C., Stathopoulos, T., Eds.; Springer, Vienna, 2011; Vol. 531 ISBN 978-3-7091-0952-6.
5. Hu, Y.; Yang, J.; Baniotopoulos, C.C.; Wang, F. A comparison of structural performance enhancement of horizontally and vertically stiffened tubular steel wind turbine towers. *Struct. Eng. Mech.* **2020**, *73*, 487–500, doi:10.12989/sem.2020.73.5.487.
6. Lavassas, I.; Nikolaidis, G.; Zervas, P.; Efthimiou, E.; Doudoumis, I.N.; Baniotopoulos, C.C. Analysis and design of the prototype of a steel 1-MW wind turbine tower. *Eng. Struct.* **2003**, *25*, 1097–1106, doi:10.1016/S0141-0296(03)00059-2.
7. Stavridou, N.; Efthymiou, E.; Gerasimidis, S.; Baniotopoulos, C.C. Investigation of stiffening scheme effectiveness towards buckling stability enhancement in tubular steel wind turbine towers. *Steel Compos. Struct.* **2015**, *19*, 1115–1144, doi:10.12989/scs.2015.19.5.1115.
8. Ashby, M.F.; Evans, A.G.; Fleck, N.A.; Gibson, L.J.; Hutchinson, J.W.; Wadley, H.N.G. Properties of metal foams. In *Metal Foams*; 2000; Vol. 4, pp. 40–54.
9. Veljkovic, M.; Heistermann, C.; Husson, W.; Limam, M.; Feldmann, M.; Naumes, J.; Pak, D.; Fabe, T.; Klose, M.; Fruhner, K.-U.; Baniotopoulos, C.. *High-Strength Tower in Steel for Wind Turbines (HISTWIN). Final Report- RFSR-CT-2006-00031*; Brussels, Belgium, 2012;
10. Simulia.DassaultSystèmes. Abaqus, Documentation and User Manual 2012.
11. EN 1991-01-04 *Eurocode 1: Actions on structures: Part 1-4: General actions-Wind actions*; Brussels, Belgium, 2005;
12. Yiatros, S.; Petrunin, I.; Fragonara, L.Z.; Brennan, F.P. *Experimental Investigation of Vibration Damping in Steel Foam Sandwich Structures. A report from a 2016 Research Award-winning project*; 2017;
13. Yiatros, S.; Marangos, O.; Votsis, R.A.; Brennan, F.P. Compressive properties of granular foams of adhesively bonded steel hollow sphere blocks. *Mech. Res. Commun.* **2018**, *94*, 13–20, doi:10.1016/j.mechrescom.2018.08.005.