



A new Tower-Concept with Sandwich-Sections

Structural Design of Sandwichtowers for Wind Energy Converters

A new kind of tower construction, calling sandwichtower, is developed for wind energy converters. The tower consists of two steel shells which are bonded together with a core material. Compared to a steeltower the plate thickness is split into an inner and outer steel face. The core between the faces increases the stability of the shells. It works together like a sandwich shell. Different composite shell theories are used to estimate the stability of such double skin shell constructions. A model scale test series with is carried out to analyse the influence of different core materials. The test specimens are loaded by uniform axial force to observe the shell buckling. The experimental results are compared to numerical simulations including measured geometrical imperfections. Within a numerical predesign the use of high strength steels for the inner and outer face is also considered to compare the various types of tower configurations. The goal is to find the best combination of steel faces with a core material in the ultimate limit state.

1 Introduction

The capacity in wind energy has been increased significantly within the last few years in Europe. Due to ongoing research and developments wind energy converters (WEC) get more and more efficient and economic. However, the requirements on the supporting structures will be also increased with the development of bigger turbines. The structural design of tubular steel towers is dominated by ultimate and fatigue limit state. Especially the shell buckling leads to high dimensions for the steel sections during the design process. Therefore, lower tower sections must be assembled with shell segments, which have often a thickness of 30 mm and more. This trend is in contrast to the fabrication costs, transportation and steel tonnages. With regard to the next generation of WEC with bigger turbines as well as larger towers new or improved solutions must be developed for tower sections with respect to stability and fatigue. This contains the choice and combination of materials for new tower variants, the increase of shell stability, innovative joint techniques, fabrication processes as well as questions to the fatigue life of each component.

2 A new tower concept

The intention of every engineer, planning steel constructions, is to increase the bearing capacity and if possible saving weights simultaneously. With regard to axially compressed steel shells the use of high-strength steels could be one opportunity for this challenge. But the comparison in Fig. 1 for buckling loads of steel tower sections (ST) with various steel grades shows that only the use of high-strength steels could not satisfy this intention. The section ST S235 has a length of $H = 30$ m, a diameter of $D = 5.5$ m and a constant shell thickness of $t = 50$ mm.



Figure 1: Comparison of tower sections with various steel grades with regard to shell buckling

For the other tower section the shell thickness can be decreased concerning the yield stress ratio. Thus, for example the comparable thickness for a steel shell with S460 can be calculated to:

$$t_{ST\ S460} = \frac{f_{y,k\ S235}}{f_{y,k\ S460}} \cdot t_{ST\ S235} = \frac{215}{460} \cdot 50 = 24\text{mm} \quad (1)$$

Therefore, the ideal buckling stresses are calculated according to DIN 18800-4 [1] and for the same boundary conditions. The buckling reduction factor κ_2 decreases with increasing the relative slenderness λ_s . As result the κ_2 of the ST S460 section with 0.61 is significant lower as for the ST S235 section with 0.93. The ratio of utilization between the real buckling stress and the yield stress falls from 85% for ST S235 to 61% for ST S460 and 31% for ST S690. Thus, only the use of high strength steels is not recommended for tower sections of WEC without any stiffeners. But nevertheless to use the increase of strength and reduction of weight due to high strength steels a sandwich cylinder offers a new alternative solution for tower sections of WEC as shown in Fig. 2. This new



kind of tower section consists of two steel shells which are bonded together with a core material. Compared to a steel tower section the shell thickness is split into an inner and outer steel face.

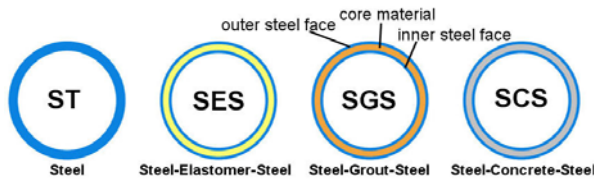


Figure 2: Sandwich shells with a core material as full space stiffener for tower sections of WEC

The core between the inner and outer steel face increases the stability of the shells. It works together like a sandwich shell. Different composite shell theories are used to estimate the stability of such double skin shell constructions. The goal is to find the best combination of steel faces with a core material in the ultimate limit state. The following variants are preferred:

- sandwich section with elastomer core (SES)
- sandwich section with grout core (SGS)
- sandwich section with concrete core (SCS)

The diameter and the shell thicknesses will be assumed constant over the section length such as done for the monocoque steel section in Fig. 1. With the idea of a double skin shell construction for WEC the following facts have to be investigated:

- increase in shell stability
- additional load capacity due to the core
- using high strength steels
- assembly two smaller shell thicknesses
- reducing steel and overall masses
- decreasing weld deposit and pre-heating
- additional injection process
- new hybrid tower variants
- new type of connections

The goal is, to find the best combination of materials and shell thicknesses to satisfy important criteria's in the design and fabrication phases. However, the economy would be playing the decisive role finally. But with this new tower concept a new kind of hybrid tower is feasible like shown in Fig. 3. This type consists of different tubular sections, where the upper section is a monocoque steel shell and the lower one is a sandwich shell construction. Compared to a monocoque construction of the same face materials, this new tower-concept produces structures with higher overall buckling loads and offers new types of connections between the sections.

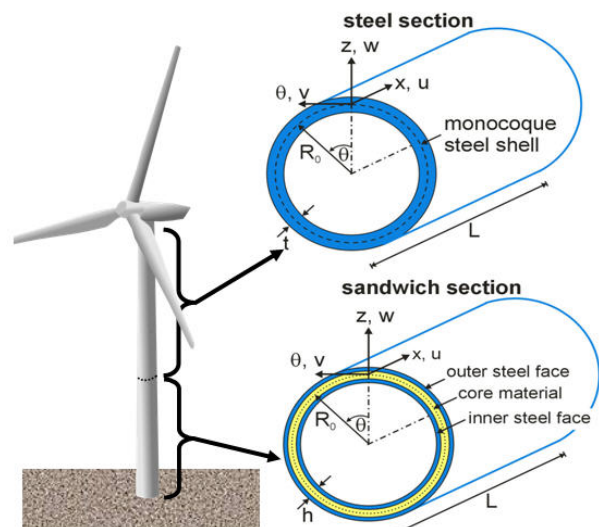


Figure 3: A new kind of hybrid tower for WEC

The following chapters deal with design criteria's in the ultimate limit state. Especially for the shell buckling of such sandwich cylinders a model scale test series is carried out to analyze the influence of suitable core materials. Furthermore the experimental results are compared to numerical simulations including measured geometrical imperfections. Within a parameter study the use of high strength steels for the inner and outer face is also considered to compare the various types of tower configurations and the overall masses.

3 Ultimate limit state

Over the years a significant literature has evolved of methods of analysis and design for sandwich constructions subjected to various mechanical and environmental loads. An overview of the methods and theories is included in [3].

The geometry of such sandwich cylinders is shown in Fig. 3 with the length L , the radius R_0 of the mid-plane and the shell thickness h . The mid-plane of the sandwich shell is used as reference surface, which is in case of symmetry the mid-plane of the core material. Thus, the core is defined as layer 0 with the thickness t_0 . The nomenclatures for the other layers with thicknesses t_{-1} for the inner steel face and t_{+1} for the outer steel face are shown in Fig. 4.

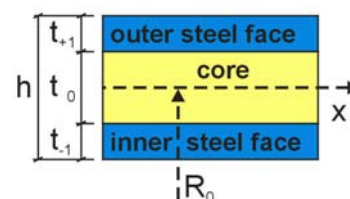


Figure 4: Definition of the geometry for a sandwich shell (x-axis in axial direction of the shell)



A parameter study is carried out to check if the classical shell theory for laminate composites in [3] is also applicable for sandwich cylinders of such tower section shown in Fig. 2. For the calculations the dimensions in Fig. 1 are used for the monocoque steel sections ST S235 and ST S460, which will be compared with two configurations for sandwich tower sections. The first sandwich construction is a combination of steel-grout-steel (SGS), where a grout is used as core material. The second one is a combination of steel-elastomer-steel (SES). In this case a polyurethane with excellent bonding characteristics is taken into account for the core. The various thicknesses and the material properties are summarized in table 1:

Type	Layer thickness $t_1 / t_0 / t_{+1}$ in mm	E-Module of core E_0 in MPa	Poisson ratio ν_0
ST S235	50	-	-
ST S460	24		
SGS S235	25 / t_0 / 25	33800	0.20
SGS S460	12 / t_0 / 12		
SES S235	25 / t_0 / 25	870	0.36
SES S460	12 / t_0 / 12		

Table 1: Parameters for the sections ST, SGS and SES

The criterion of shell buckling plays a decisive role for the structural design of tower sections. Typical steel sections of WEC with a ratio between $r/t = 60 - 100$ have allowable characteristic or real buckling stress $\sigma_{x,Rk}$ which are usually lower than the yield stress $f_{y,k}$. Herein, the real buckling stress depends on the relative slenderness of the shell, the type of loading and the class of imperfection. For axial compression the buckling reduction curve κ_2 has to be used in Germany [1]. A cylindrical steel shell can be optimized so that no reduction of the yield stress is necessary. This level is reached if the relative slenderness is lower or equal 0.25 [1]:

$$\bar{\lambda}_{sx} = \sqrt{\frac{f_{y,k}}{\sigma_{x,cr}}} = 0.25 \quad \text{for } \kappa_2 = 1.0 \quad (2)$$

Thus, for each cylindrical steel shell loaded by axial compression the optimized elastic critical buckling stress $\sigma_{x,cr,opt}$ can be estimated for every kind of steel grade.

For the sandwich shells a linear buckling analyses is carried out to estimate the core thickness, which is necessary to get these optimized elastic critical buckling stresses. All results of the parameter study are summarized in Fig. 5 to compare the critical buckling stresses derived from numerical simulations with values of shell theories for monocoque shells and sandwich shells. Therefore, the results for SGS and also for SES agree very well based on the chosen

configuration of face and core thicknesses. To check a wide range the core thicknesses is varied between $t_0 = 0 - 80$ mm.

Therefore, a sandwich shell with steel faces of S460 has an optimized elastic critical buckling stress estimated to $\sigma_{x,cr,opt} = 7360$ MPa. This value is also plotted as limit line in Fig. 5, which is crossed due to the curve for SGS S460 nearly $t_0 = 68$ mm. This is the core thickness that belongs to the optimized configuration for the sandwich tower section SGS using high strength steel faces with $t_1 = t_{+1} = 12$ mm.

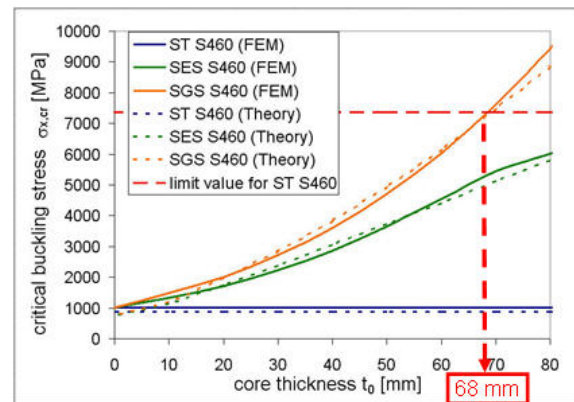


Figure 5: Comparison of critical buckling stresses for S460 depending on the core thickness

Since the tower sections for WEC are normally designed in the elastic range it is not recommended or necessary to increase the buckling stresses and core thicknesses over the optimized values.

With these optimized core thicknesses the steel faces can be utilize up to the yield stress and no reduction due to shell buckling is necessary in the elastic range. A comparison for the real buckling loads in Fig. 6 shows the increase in shell stability which is possible with sandwich tower sections in contrast to monocoque steel tower sections.

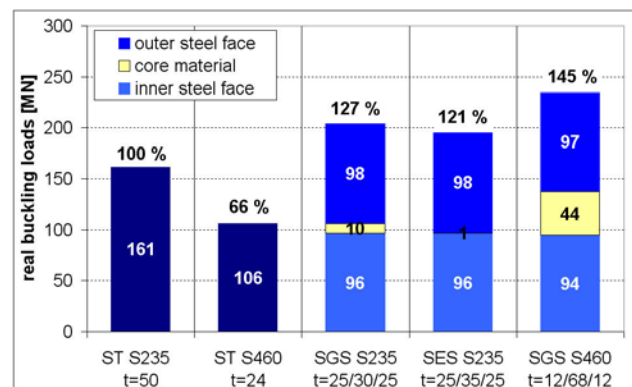


Figure 6: Increase of buckling loads with sandwich tower sections

Herein, the real buckling loads are calculated with regard to DIN 18800-4 where the steel cylinder ST



S235 is defined as reference type with 100 % buckling load. In comparison to the reference cylinder ST S235 in Fig. 6 the ST S460 has a significant lower buckling load (-30%). Thus, the ST S460 would be not economic and is cancelled as an alternative solution for tower sections.

But with sandwich tower sections a significant increase in overall buckling loads is possible. For example the buckling load of SES S235 is with 195 MN (+21%) much higher as for the reference cylinder ST S235. The value for SGS S235 is even 204 MN which is an increase of 27% compared to the reference type. It has to be mentioned that the buckling loads correspond to the bearing capacity in the ultimate limit state, since no reductions due the overall shell buckling are necessary. Therefore, the load capacities of the core materials are additionally considered in Fig. 6. Herein, the compressive strength of the grout material is much higher as for the elastomer core. Thus, the ratio of load capacity is higher for the SGS S235 as for the SES S235. With regard to the economy the additional load capacity of the cores is beneficial or even necessary to justify the extra costs for this core material.

With these assumptions a further increase would be possible with the configuration as SGS S460. In this case the steel faces can be also loaded up to the yield strength and the load capacity of the core material increases according to the stress strain relation and due to the higher core thickness. This type of tower section is very interesting because simultaneously to the increase in bearing capacity a reduction in overall mass is possible as shown in Fig. 7.

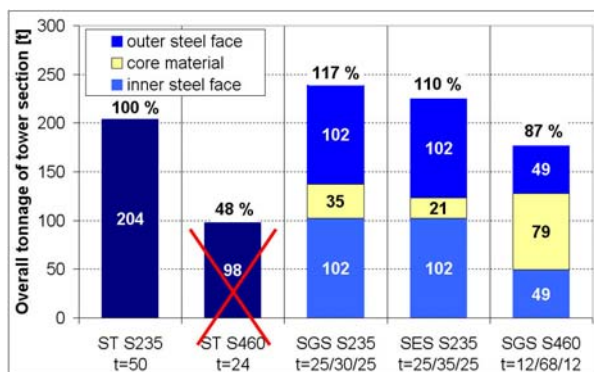


Figure 7: Comparison of tonnage between the sections

The intention of every planning engineer to increase load capacities coupled with saving tonnage, as formulated in the introduction, seems to be possible with sandwich shells for tower sections of WEC. The comparison of tonnage in Fig. 7 is based on the following mass densities:

- Steel: $\rho_S = 7850 \text{ kg/m}^3$
- Grout: $\rho_G = 2280 \text{ kg/m}^3$
- Elastomer: $\rho_E = 1150 \text{ kg/m}^3$

The ST S235 with 50 mm shell thickness has been defined as reference tower section with 100 % tonnage again. The higher buckling loads for SGS S235 and SES S235 are only possible with additional tonnages due the core material. But the use of the high strength steel S460 in combination with a grout material as core the tonnage can be decreased (-13%). Together with the increase in buckling loads (+45%) the SGS S460 is a more lightweight structure with great shell stability compared to the ST S235 and offers a very interesting new alternative solution for tower sections.

However, in the comparison it has also to be taken into account that two cylindrical steel shells for one sandwich tower section have to manufacture which produces higher costs. Additionally the costs for the injection process of the core material have to be considered. On the other side there are saving in costs for welding possible because the volume for the seam welds decreases in square with the shell thickness. In comparison to a reinforced concrete tower section a sandwich tower section has the advantage that the steel faces function as formwork shells during the production process.

The design study above is carried out only for axially compressed tower sections, but also the other loads of WEC such as bending and torque has to be taken into account. The nodding moment, the torsion and the thrust of the turbine dominate the stresses in the tower sections. Therefore the laminate shell theory presented in [3] is also applicable.

In contrast to conventional composite structures where shear connectors are used the forces between the layers of a sandwich cylinder should be transferred over adhesion. This criteria that the adhesive bonding between the steel faces and the core is ensured at the whole contact area in the elastic range up to yield stress of the steel faces, has been assumed for the design study above. Whether this assumption is justified was the interest of a buckling test series at the Institute for Steel Construction of the Leibniz University Hannover. The experimental results of this test series are presented in the next chapter.

4 Shell buckling tests

A model scale test series with sandwich cylinders was carried out to analyze the shell buckling and the influence of different core materials. The test specimens are loaded by uniform axial compression. The deformations and strains are measured online by optical 3D sensors to localize critical zones. The buckling tests were carried out on a 600 kN servo hydraulic testing machine. The test setup is shown in Fig. 8. The test specimen has a top and a bottom plate at the ends and is vertical positioned between the supporting elements.

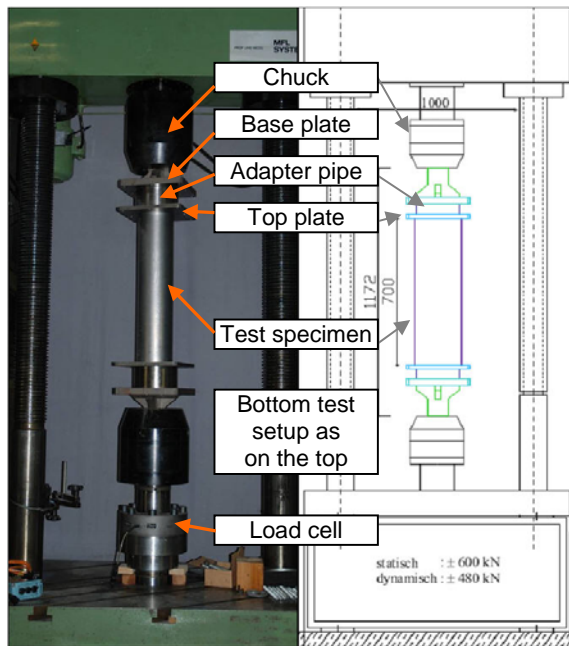


Figure 8: Test setup for sandwich shell buckling tests

As core three different injectable materials were tested. The most important mechanical properties of all core materials are listed in Table 2.

Company	Core material	E_0	f_{ck} after 1 day	f_{ck} after 28 day
		[MPa]	[MPa]	[MPa]
Sika	Grout 311	37000	28	78
Pagel	V1/10	35300	39	91
Elastogran	Elastomer	870	18	18

Table 2: Parameters of core materials [2]

Since two different grout materials based on mineral components were tested, the type SGS (steel-grout-steel) gets the extensions SGS_s for Sika and SGS_p for Pagel. As steel material with a yield stress of 235 MPa was used for inner and outer steel shells. The geometric data of the tested cylinders are summarized in Table 3. All test specimens have a length (height) of 700 mm. In addition to the buckling tests with sandwich cylinders the inner and outer steel shells were also used for stand alone tests as steel cylinders. Therefore, the inner steel shell with 0.7 mm was ST_1 and the outer steel shell with 0.8 mm was ST_2.

Type of cylinder	Length L	Radius R_0	Layer $t_{-1} / t_0 / t_{+1}$
	[mm]	[mm]	[mm]
ST_1	700	72.55	0.7
ST_2		84.20	0.8
SGS_s		78.40	0.7 / 10.9 / 0.8
SGS_p			
SES			

Table 3: Geometry of test specimens

The layer configuration for the sandwich cylinders is fixed due the geometry of inner and outer steel shell. Thus, the core has a thickness of 10.9 mm. It has to be mentioned that the core thickness can not be too thin for the model scale tests because the core materials must be injectable. The injection processes are shown in Fig. 9.

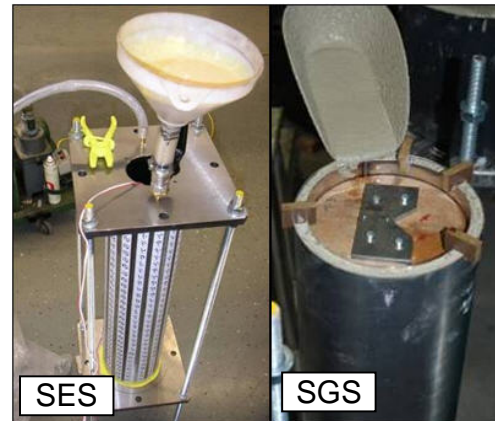


Figure 9: Injection of core materials for SES and SGS

The buckling tests were carried out after the optical measurements of geometrical imperfections for all test specimens and the injection processes. Both sandwich cylinders with grout as core material (SGS_s and SGS_p) were tested one day after injection. All buckling tests were carried out displacement controlled. During the tests the strains were measured using strain gauges attached to the outer surface of the cylinders. The displacements in axial direction were recorded online by inductive sensors. The applied axial force was measured with a load cell. All test results of shell buckling are summarized in Fig. 10.

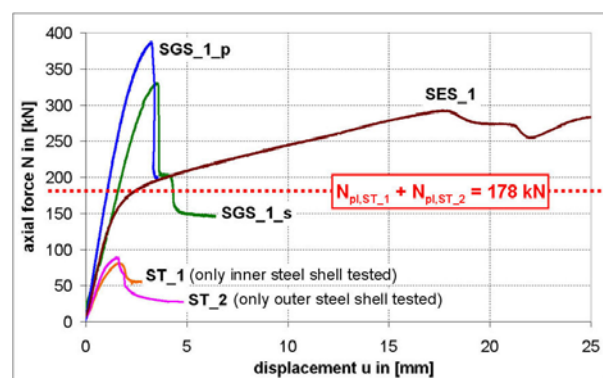


Figure 10: Buckling tests with steel and sandwich cylinders [2]

The axial force could be increased for the sandwich cylinders. The buckling loads of all sandwich test specimens were over the limit of elasticity of the steel faces which is estimated to 178 kN ($N_{pl,ST_1} = 75$ kN from inner steel face and $N_{pl,ST_2} = 103$ kN from outer



steel face). The buckling loads of SGS_p and SGS_s are very high (356 and 306 kN).

These test results attest that the grout materials participate at the bearing capacity as known from composite columns. For both sandwich variants with grout the same post buckling behavior can be observed as the steel variants. The sudden drop (collapse) in bearing capacity is typical for buckling modes of shells under axial compression. But in contrast to this the SES with an elastomer core has a very good post buckling behavior. This kind of stability based mainly on the excellent bonding characteristics of the elastomer which could also transfer the forces between the layers in the plastic range of the steel shells. Furthermore, it can be recognized that the nonlinearity of the SES-curve started near 180 kN which corresponded approximately to the limit of elasticity for the steel faces. This can be explained with the lower stiffness and the lower compressive strength of the elastomer core. It is weaker compared to the core with grout materials.

The stability of sandwich shells can be mainly optimized with the thickness, the module of elasticity and the compressive strength of the core material. Since elastic shell buckling could be avoided other failure modes occurred in the plastic range of the sandwich cylinders for example face wrinkling as shown in Fig. 11.



Figure 11: Face wrinkling of a sandwich cylinder (SGS)

Face wrinkling can occur in a sandwich construction either when subjected to a compressive buckling or in the compressive face during bending. A wrinkle that becomes unstable causes an indentation in the core if the compressive strength of the core is lower than the tensile strength. The second mode of face wrinkling is possible if the wrinkle causes a gap between the core and the faces if the tensile strength of the core is lower than the compressive strength. Whichever case applies, a poor adhesive core will undoubtedly reduce the allowable wrinkling stress of the sandwich. In Fig. 11 it can be recognized that the second mode of face wrinkling occurred where the wrinkle cause a gap between the core and the steel faces. Outside of the area of face wrinkling the bonding was intact for all tested sandwich cylinders.

As result the shell stability of sandwich constructions could be ensured up to the limit of elasticity with sufficient bonding behaviors for all tested core materials. The increase in buckling loads was very high and the steel faces could be stressed over the yield strength. Furthermore, the additional bearing capacity due to the core materials in the elastic range offered a further increase in buckling loads compared to monocoque steel constructions.

Comparisons with numerical simulations and sandwich shell theories were already presented by the authors at the European Wind Energy Conference EWEC 2008 in Brussels [2].

Conclusions

Alternatively to a steel tower section for WEC a sandwich tower section was analyzed with regard to the stability. At first a comparison between cylindrical shells with various steel grades showed that a shell with high strength steels has a lower buckling load if the shell thickness is reduced according to the ratio of yield stresses. Thus, a monocoque steel shell with S460 or S690 would be not economic without any stiffeners and is not recommended as an alternative solution for tower sections of WEC. But with sandwich shells in combination with high-strength steels a significant increase in overall buckling loads is possible.

The sandwich shell consists of an inner and outer steel face, which were bonded to a suitable core material between them. Two grout and one elastomer core were investigated. A parameter study with linear buckling analyses showed a significant increase in shell stability for sandwich cylinders. Therefore, the inner and outer steel faces could be loaded up to the yield stress considering an optimized core thickness. In this case the core materials operated as full space stiffener and produced an increase of critical buckling stresses. The goal was to find the best combination of steel faces with a core material in the ultimate limit state for sandwich tower sections of WEC. Due to the reached plastic buckling loads the combination of high-strength steels is in principle possible to get tower sections, which will be optimized with regard to stability and weight. The design study was carried out only for axially compressed tower sections, but also the other loads of WEC such as bending and torque has to be taken into account.

Several buckling tests were carried out to check the bonding characteristics and ultimate bearing capacities of sandwich cylinders. The test series showed a significant increase in buckling load capacity, which also depends on the compressive strength of the core materials. The failure criteria for all variants of tested sandwich shells is more a local failure due to face wrinkling in the plastic range and not due to an overall shell buckling. As result the shell



stability of sandwich constructions could be ensured up to the limit of elasticity with sufficient bonding behaviours for all tested core materials.

Furthermore, a comparison between theory, experiment and simulation was carried out. As result the consideration of additional load capacities due to the core materials was valid. Thus, the sandwich shells in combination with high-strength steels could be offered a new alternative solution for tower sections of WEC.

However, the fatigue limit state must be also considered. Therefore, a method for post weld treatment is preferred to increase the fatigue strength of the steel faces. Furthermore, new joint techniques are also needed for hybrid tower constructions with sandwich sections.

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Prof. Schaumann researches in the field of wind energy at the institute for steel construction since many years. A lot of projects with governments and industrial partners are carried out to enhance the ultimate and fatigue limit state of support structures and connections for WEC. He is a member of ForWind and of the European Wind Platform in the working group for Offshore Developments.

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