Structural Design of Hybrid-Towers for Wind Energy Converters

Prof. Dr.-Ing. Peter Schaumann
ForWind – Center for Wind Energy Research
Institute for Steel Construction
Leibniz Universität Hannover, Germany
schaumann@stahl.uni-hannover.de

Dipl.-Ing. Christian Keindorf
ForWind – Center for Wind Energy Research
Institute for Steel Construction
Leibniz Universität Hannover, Germany
keindorf@stahl.uni-hannover.de

Abstract

The structural design of sandwich towers for wind energy converters is presented in this paper. This new kind of hybrid tower consists of two steel shells which are bonded together with a core material. Compared to a steel tower section the shell thickness is splitted to an inner and outer steel face. The core between the inner an outer steel face increases the stability of the shells. It works together like a sandwich or composite shell. Different composite shell theories are used to estimate the stability of such double skin shell constructions. A model scale test series with sandwich cylinders is carried out to analyse 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 experimental results are compared to numerical simulations including measured geometrical imperfections. The FE-model is validated by a composite shell theory. Within a numerical pre-design the use of high strength steels for the inner and outer steel face is also considered to compare 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. However, the fatigue limit state must be also considered. Therefore, a method for post weld treatment will be presented to increase the fatigue strength of the steel faces. Furthermore, new joint techniques are also suggested for hybrid tower constructions with sandwich sections.

Keywords: hybrid, tower, sandwich, shell buckling, fatigue, grouted connection

1 Introduction

Wind energy represents an important sector of renewable energy sources. The capacity in wind energy has 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 tower constructions are usually manufactured as tubular steels or pre-cast concrete segments or lattice structures. The structural design of steel towers is dominated by ultimate and fatigue limit state. Especially the shell buckling leads to high dimensions for tubular 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 facilities and steel tonnages.

Furthermore, the bolted ring flange connections, which are used to joint the tower sections to each other, reach huge dimensions for multi megawatt turbines. The eccentric position of the bolts in this type of connection leads to a complex load-carrying behaviour. The effort for production, erection and maintenance of such bolted ring flange connections is very high. In addition they have to be inspected for fatigue cracks, imperfections and lost of pre-tension.

With regard to the next generation of WEC with bigger turbines as well as larger towers new or improved solutions have to be developed for tower sections and connections 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

A new tower concept is presented in this paper as an alternative solution to the conventional tower variants and joint techniques.
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 cylindrical steel tower sections (ST) with various steel grades shows that only the use of high-strength steels could not satisfy the intention.

Steel grade	S 235	S 355	S 460	S 690
$f_{y,k,red}$ [MPa]	215 for t=50	345 for t=35	460 for t=24	690 for t=16
$\sigma_{x,cr}$ [MPa]	2011	1459	1032	706
λ_S [-]	0.33	0.49	0.67	0.99
κ_2 [-]	0.93	0.78	0.61	0.31
$\sigma_{x,cr,k}$ [MPa]	199	269	280	215
$\sigma_{x,cr,k}$ / $f_{y,k}$ [%]	85 %	76 %	61 %	31 %

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

The section ST S235 has a length (or height) of H = 30 m, a diameter of D = 5.5 m and a constant shell thickness of t = 50 mm. Because the thickness is greater than 40 mm the yield strength f_{yk} has to be reduced from 235 to 215 MPa with regard to EN 10025-2 [4]. 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:

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

Therefore, the ideal buckling stresses are calculated according to DIN 18800-4 [1] and for the same boundary conditions (BC 2 at the bottom and top of the sections). The buckling reduction factor κ_2 has to be used for axially compressed shells, which depends on the relative slenderness of shells λ_S. The buckling reduction factor decreases with increasing the relative slenderness. 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.

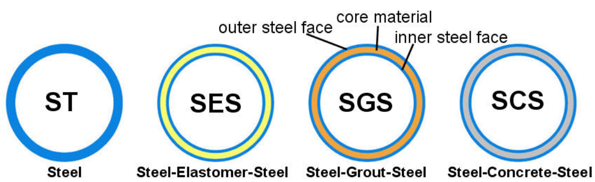

Figure 2: Sandwich shells with a core material as full space stiffener for tower sections of WEC

The new sandwich tower sections consist of two steel shells (inner and outer steel face) which are bonded together with a core material. 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 all 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. The hybrid tower 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 steel section the shell thickness is divided into an inner and outer steel face. The core between them increases the stability of the shells. Therefore, the use of a sandwich

construction, compared to a monocoque construction of the same face material, produces structures with much higher overall buckling loads and offers new types of connections between the sections.

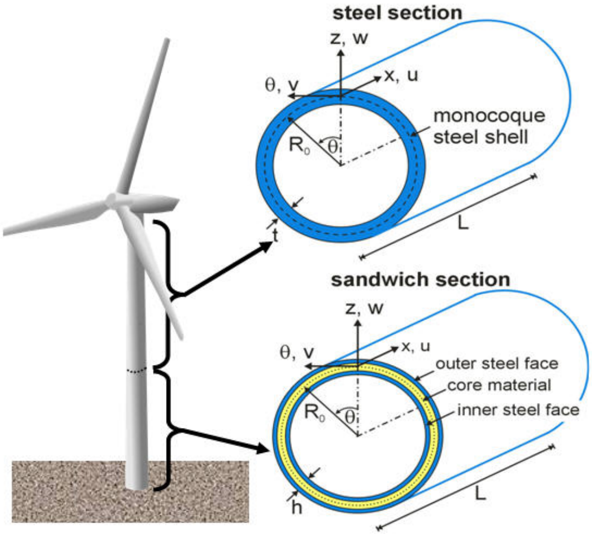

Figure 3: A new kind of hybrid tower for WEC

The following chapters deal with design criteria's in the ultimate and fatigue 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. Finally a new type of connection for hybrid towers with sandwich sections is presented in this paper.

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 [5] and [9]. To analyze the stability of sandwich cylinders the laminate composite shell theory is used presented by Vinson in [9]. Therefore, effects of anisotropy and asymmetry to the mid-plane of sandwich shell cross section can be considered. The details and the application of the sandwich shell theory for tower section are already presented in [8].
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 definition for deformations (u, v, w) is based on the cylindrical coordinate system (x, θ, z). 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.

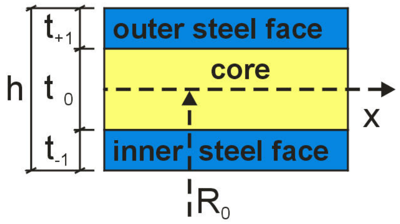

Figure 4: Definition of the geometry for a sandwich shell (x-axis in axial direction of the shell)

A parameter study is carried out to check if the classical shell theory for laminate composites in [9] 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]:

$$\sigma_{x,Rk} = \kappa_2 \cdot f_{y,k} \quad (2)$$

A cylindrical steel shell can be optimized so that no reduction of the yield stress is necessary as shown in Fig. 5. This level is reached if the relative slenderness is lower or equal 0.25 [1]:

$$\bar{\lambda}_{Sx} = \sqrt{\frac{f_{y,k}}{\sigma_{x,cr}}} = 0.25 \qquad \text{for } \kappa_2 = 1.0 \quad (3)$$

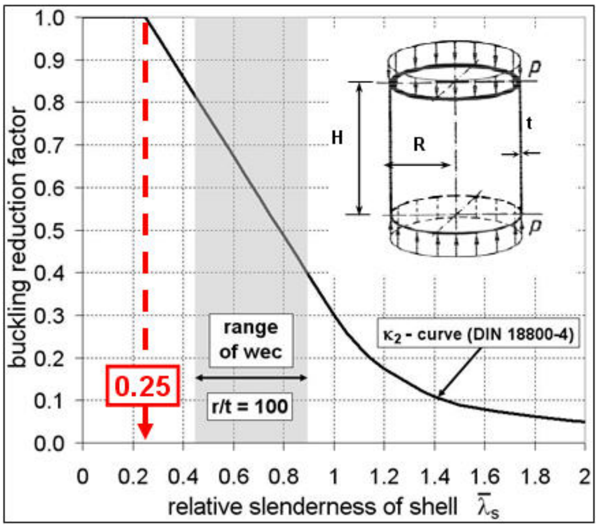

Figure 5: Buckling reduction curve κ_2 for cylindrical shells loaded by axial compression [1]

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 as follows:

$$\sigma_{x,cr,opt} = \frac{f_{y,k}}{\left(\bar{\lambda}_{Sx}\right)^2} = \frac{f_{y,k}}{0.25^2} = 16 \cdot f_{y,k} \quad (4)$$

In this way the best configuration concerning the shell stability and utilization in the elastic range would be reached if the following elastic critical buckling stresses are:

- for S235: $\sigma_{x,cr,opt}$ = 3760 MPa
- for S355: $\sigma_{x,cr,opt}$ = 5680 MPa
- for S460: $\sigma_{x,cr,opt}$ = 7360 MPa

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. 6 to compare the critical buckling stresses derived from numerical simulations with values of shell theories for monocoque shells according to [1] and composite shells presented by Vinson in [9]. 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. Thus, the numerical and theoretical results are plotted in Fig. 6.

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. 6, 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.

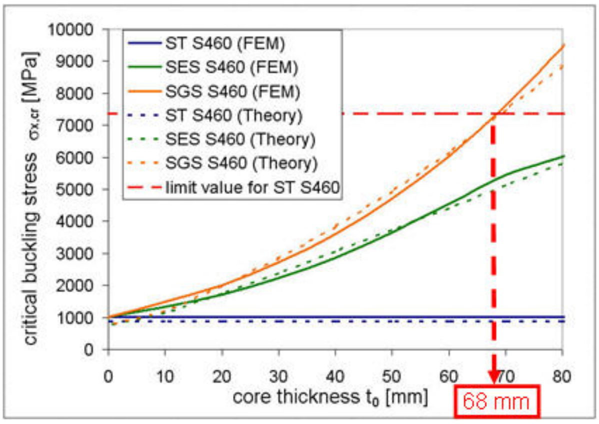

Figure 6: Comparison of critical buckling stresses for S460 depending on the core thickness

Because the SES with an elastomer core is weaker the optimized core thickness would be nearly 100 mm. 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. For the sandwich tower section with S235 the optimized critical buckling stress (3760 MPa) is reached when t_0 = 30 mm for SGS S235 and t_0 = 35 mm for the SES S235 (not plotted in Fig. 6).

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 (s. Eqs. 3 and 4). A comparison for the real buckling loads in Fig. 7 shows the increase in shell stability which is possible with sandwich tower sections in contrast to monocoque steel tower sections. Herein, the real buckling loads are calculated with regard to DIN 18800-4 [1] where the steel cylinder ST S235 is defined as reference type with 100 % buckling load.

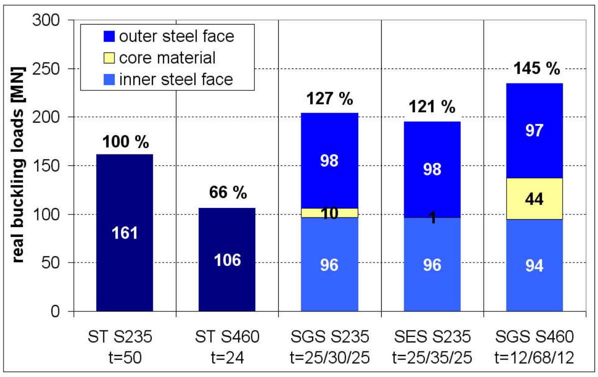

Figure 7: Increase of real buckling loads with sandwich tower sections

In comparison to the reference cylinder ST S235 in Fig. 7 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. 7. 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. The values are estimated in the elastic range according to [2] for composite structures. But this national standard is not applicable for all structural design calculations of the sandwich construction because of the higher slenderness the cylinders can not be declared as composite column structures. However, the stress-strain relations can be used and they are valid up to the limit of elasticity which is also the design limit for supporting structures of WEC. Furthermore, with regard to the economy the additional load capacity of the grout core 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. 8. 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.

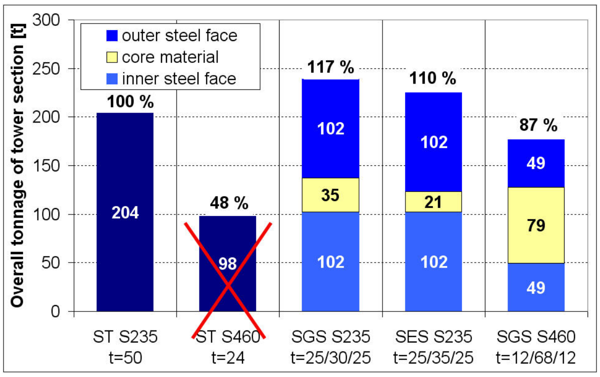

Figure 8: Comparison of tonnage between the sections

The comparison of tonnage in Fig. 8 is based on the following mass densities:

- Steel: ρ_S = 7850 kg/m³
- Grout: ρ_G = 2280 kg/m³
- Elastomer: ρ_E = 1150 kg/m³

The ST S235 with 50 mm shell thickness has been defined as reference tower section with 100 % tonnage again. The use of high strength steel leads to a reduction, the ST S460 weights only 48 %. But the buckling load of this type is to low in contrast to the reference cylinder (s. Fig. 7). Thus this tower section without any stiffeners is cancelled for an alternative design study.

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.

The optimization can also be carried out with the goal to find the best configuration with the same buckling load (161 MN = 100 % of ST S235). In this way the optimized layer combination for SGS S460 would be t_{-1} / t_0 / t_{+1} = 8 / 60 / 8 mm with only 135 tons. The reduction in overall weight is then calculated to -34 %. The steel tonnage falls from 204 t for S235 to 65 t for S460. Considering the actual prices for the steel grades there would be enough saving in costs to cover the additional costs for the grout material.

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.
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 [9] is also applicable. For example the buckling due to torsion and a comparison between the buckling loads for various monocoque and sandwich tower sections is already presented in [8].
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. Furthermore, the hoping effect of the steel faces to the core material is also an advantage for the new tower concept.
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. Herein, various sandwich cylinders were loaded with uniform axial compression. The experimental results of this test series are presented in the next chapter.

4 Shell buckling tests

The buckling tests with axial compression at sandwich cylinders were carried out on a 600 kN servo hydraulic testing machine. The test setup is shown in Fig. 9.

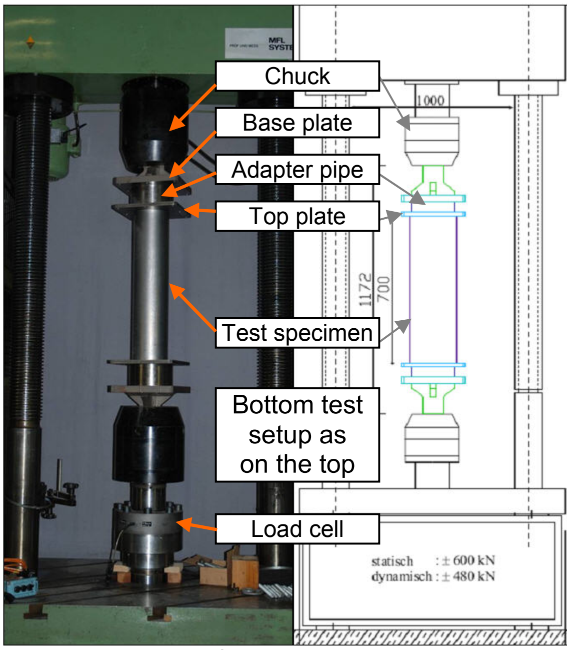

Figure 9: Test setup for sandwich shell buckling tests

The test specimen has a top and a bottom plate at the ends and is vertical positioned between the supporting elements. The axial force is induced over base plates and measured with a load cell. Adapter pipes were used between the base and top plates to get a uniform pressure in circumferential direction. In addition, top and bottom plate have circular slots according to the diameter of the test specimen to ensure ideal supporting conditions.

As core three different injectable materials were tested. The first grout was the SikaGrout 311 from Sika Deutschland GmbH, the second one was V1/10 from Pagel Spezialbeton GmbH, both consist of mineral components. Additionally an elastomer (two-component polyurethane) from Elastogran GmbH was used as core material. The most important mechanical properties of all core materials are listed in Table 2.

Company	Core material	E_0	f_{ck} after 1day	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 [6]

The values for the module of elasticity E_0 are taken from the datasheets of the companies. In contrast to both grout materials the elastomer has a significant lower value, thus the elastomer core is much weaker. The values for the compressive strength after 1 and 28 days were measured in the

laboratory. After one day the grout materials have already a high early-strength. The compressive strength of the elastomer depends on the temperature but after 1 day nearly 90 % of the final strength is reached for the composite material with excellent bonding characteristics. The high early-strength is important for injection processes in situ. Both grout materials have the mass density of 2280 kg/m³ as already used for the calculations in the parameter study. The elastomer core with a mass density of 1150 kg/m³ has an advantage with regard to the comparison of tonnage.
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 the X2CrTi12 was used for inner and outer steel shells. The yield stress of this steel grade corresponds to a S235. The measured yield strength is 236 MPa and the tensile strength is 432 MPa at a strain at failure of 34 %.
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. These thin steel faces were chosen to get a high slenderness for elastic shell buckling. The steel cylinders ST_1 and ST_2 were also useful to check if the test setup was suitable for shell buckling tests.

Type of cylinder	Length L	Radius R_0	Layer thicknesses 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. Therefore, the maximum grain size for both grouts was 1 mm and for the elastomer core significant lower as 1 mm, which is an advantage for this composite material. The injection processes are shown in Fig. 10.

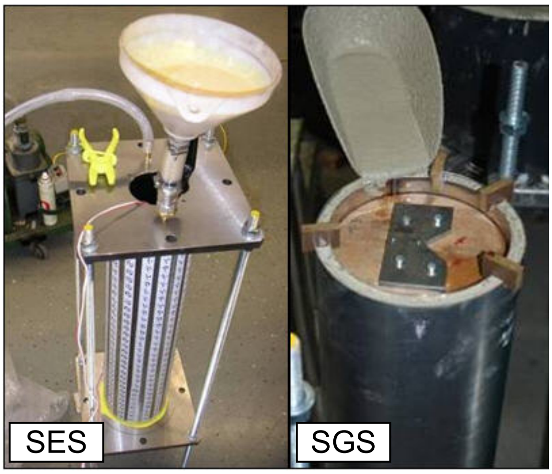

Figure 10: Injection of core materials for SES and SGS

The injection process of the elastomer was carried out with bottom and top plate to ensure a closed cavity. The elastomer was filled in with an inlet valve. At the outlet valve a vacuum pump was used to support the injection. After 10 minutes coupling processes of the two components of the elastomer began. During this exothermic reaction the elastomer expands (6 % of core volume). Due to this expansion it is ensured that the elastomer is bonded at the whole contact area to the steel faces. The maximum measured temperature was 85°C and 6 hours after injection the sandwich cylinder (SES) reached the room temperature again.
The injection of both grout materials was carried out without the top plate (s. Fig. 10). A closed cavity was in these cases not necessary. The shrinkage of the grout materials can be compensated with additive. All injection processes could be carried out without any problems. Some cuts at the sandwich cylinder after the buckling tests approved the correct bonding without any holes or leaks.
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. 11. 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). The higher value for SGS_p can be explained with the higher early-strength of the Pagel Grout V1/10 compared to the Sika Grout 311 in Table 2.

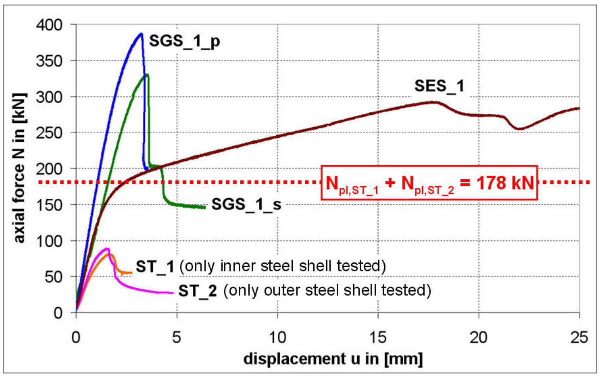

Figure 11: Buckling tests with steel and sandwich cylinders [6]

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 – no significant reduction in bearing capacity appeared. The axial force could be increased up to 293 kN by a displacement of 18 mm. 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. 12.

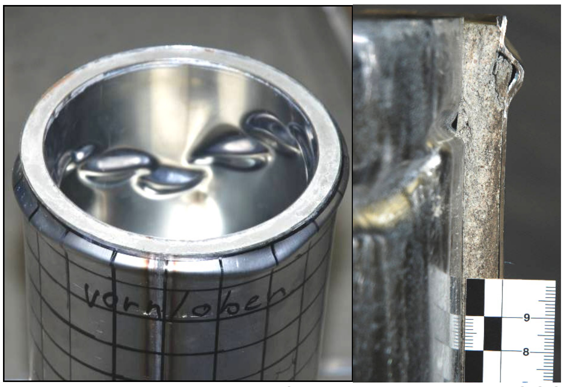
Figure 12: Face wrinkling of a sandwich cylinder (SGS)

Face wrinkling can occur in a sandwich construction either when subjected to a compressive buckling or in the compressive face during bending (s. Fig. 13). 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.

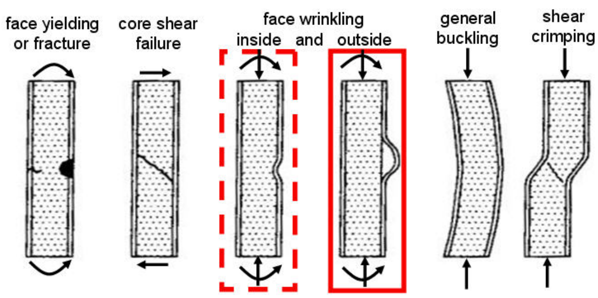

Figure 13: Failure modes for sandwich constructions [10]

After buckling tests the top plate of the SGS_s was opened and additionally a longitudinal cut was done to check the cross section and the bonding between the layers. In Fig. 12 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.

In addition to the buckling tests numerical simulations were carried out to analyze the sandwich shell buckling modes and to compare it with test results. In contrast to typical geometrically and materially nonlinear buckling analysis with included imperfections (GMNIA) these numerical simulations were executed with measured real geometrical imperfections. For example the load-displacement-curves were compared for the SGS and SES in Fig. 14.

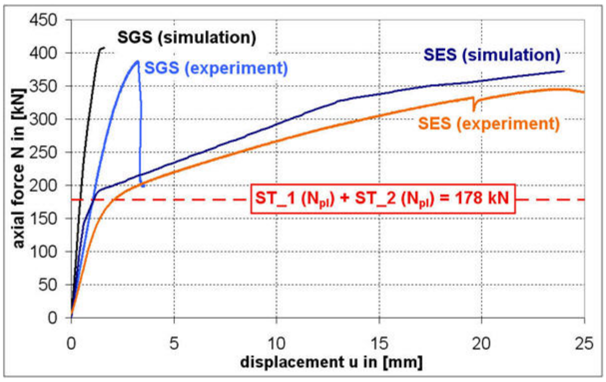

Figure 14: Comparison of load-displacement-curves

The curves estimated numerically are more stiffener in the elastic range as both tested sandwich cylinders. The difference can be explained with additional deformations of the test setup. Especially the delayed deformations in the ring slots of the top plates were also recorded of the test machine as total displacement. However, the qualitative run of the curves agree is quite good. The nonlinearity at SES starts at the same load level (180 kN) and also the slope in the plastic range corresponds to the test results. The FE-model must be extended with contact elements to simulate interface delamination as face wrinkling where a gap between the layers can be occurred. Therefore, the values have to be determined for maximum allowable tensile contact pressure and the maximum friction stress of the core materials.

Finally a comparison between theory, experiment and simulation was carried out for all steel and sandwich cylinders. For the steel shells the experimentally estimated buckling loads were over the minimum values of the German recommendation in [1] which were chosen as theoretical results. The numerical results calculated with GMNIA-buckling analyses including real geometrical imperfections have a good agreement with the test results (s. Fig. 15).

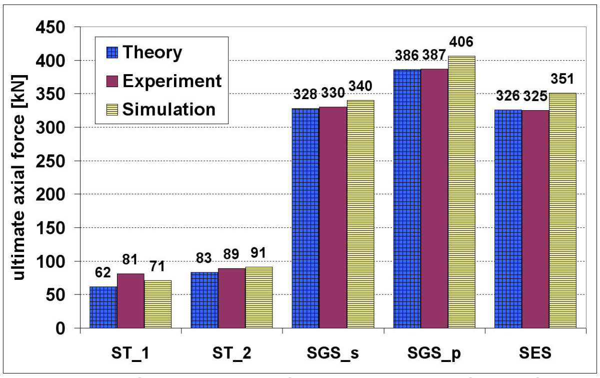

Figure 15: Comparison of ultimate axial force for all tested cylinders

As theoretical values for the sandwich shells the axial force at the strain of failure was chosen. Therefore, the proportionate axial forces of each layer were determined with the following equation based on the measured stress-strain-relations.

$$N_{theory} = A_{-1} \cdot \sigma_{-1}(\varepsilon) + A_0 \cdot \sigma_0(\varepsilon) + A_{+1} \cdot \sigma_{+1}(\varepsilon) \tag{5}$$

The calculation of the theoretical results for SGS and SES in Fig. 15 are summarized in Table 4. The values for N_{theory} agree very well to the measured axial loads (N_{exp}) compared for the point at failure (displacement, strain).

Parameter	SGS_s	SGS_p	SES
$A_{-1}/A_0/A_{+1}$ [mm²]	365 / 5369 / 370		
u at failure [mm]	3.6	3.3	18.0
ε at failure [%]	0.51	0.47	2.57
$\sigma_{-1}/\sigma_0/\sigma_{+1}$ [MPa]	242/28/242	241/39/241	313/18/313
$N_{-1}/N_0/N_{+1}$ [kN]	88/150/90	88/209/89	114/96/116
N_{theory} [kN]	328	386	326
N_{exp} [kN]	330	387	(293) 325

Table 4: Bearing capacity of sandwich variants

The comparison shows that the consideration of additional bearing capacities due to the core materials is valid, which offers a good performance concerning the sandwich shell stability of tower sections.

5 Fatigue limit state

Additionally to the ultimate limit state (ULS) the fatigue limit state (FLS) must be considered for supporting structures of WEC because the tower sections and the connections between them are dynamically loaded by wind and waves. Since the sandwich sections shall be manufactured without any bolted ring flange connections the number of hot spots for fatigue cracks can be minimized. Therefore, the focus in this paper is at the welded joints, which will be further required between the single shell segments.

For example the transverse butt weld in circumferential direction between two shell segments has normally the fatigue class (FAT) $\Delta\sigma_C = 90$ MPa according to the IIW recommendations [11]. The maximum number of cycles N can be estimated for each defined load spectrum block with regard to the following S-N curve:

$$\log(\mathrm{N}) = \log(\mathrm{a}) - \mathrm{m} \cdot \log(\mathrm{f_t} \cdot \Delta\sigma) \tag{6}$$

Due to the thickness effect the fatigue resistance of welded joints has to be reduced for plates thicker than 25 mm:

$$\mathrm{f_t} = \left(\frac{\mathrm{t}}{25\mathrm{mm}}\right)^{0.25} \tag{7}$$

For example the thickness factor for a steel tower ST S355 with a shell thickness of t = 35 mm would be $f_t = 1.1$. Thus the maximum allowable value for the damage equivalent stress is calculated to 82 MPa for the ST S355 (s. Fig. 16). If the shell thickness is splitted in an outer and inner steel face ($t_{-1} = t_{+1} = t/2$) no reduction of fatigue resistance is necessary. This is a slight advantage for double skin construction like sandwich sections. But if high strength steels are used for the faces the stress range increased with the decreased shell thicknesses. For the same load level or damage equivalent load the stress range is estimated to 120 MPa for a sandwich section with S460. Therefore a fatigue class FAT 125 is needed, which is very high. For the S690 with a comparable stress range of 180 MPa no fatigue class exist. Thus, a steel or sandwich tower section with S690 is cancelled in this parameter study (s. Fig. 16).

steel grade	S 355	S 460		S 690	
tower concept	ST	ST	SGS / SES	ST	SGS / SES
t [mm]	35	24	12-60-12	16	8-80-8
$f_{y,k}$ [MPa]	345	460	460	690	690
f_t [MPa]	1.1	1.0		1.0	
$\Delta\sigma_c$ [MPa]	82	120		180	
needed FAT class	90	125			

Figure 16: FAT classes for sandwich tower sections

But for a sandwich tower section with S460 a fatigue design is possible when the fatigue strength could be increased to the FAT 125. For example the fatigue resistance can be significant enhanced with methods of post weld treatment. One of these is the Ultrasonic-Impact-Treatment (UIT), which comprises a handheld tool and an electronic control box (s. Fig. 17). It operates with a mechanic frequency of 200 Hz overlain by an ultrasonic frequency of 27000 Hz. This method involves post-weld deformation by impacts from indenting needles at the weld toe. The objective is to introduce beneficial compressive residual stresses at the weld toe and to reduce stress concentration by improving the weld toe profile [13]. Furthermore, the area being treated is highly plastically deformed, which has the effect of work hardening.

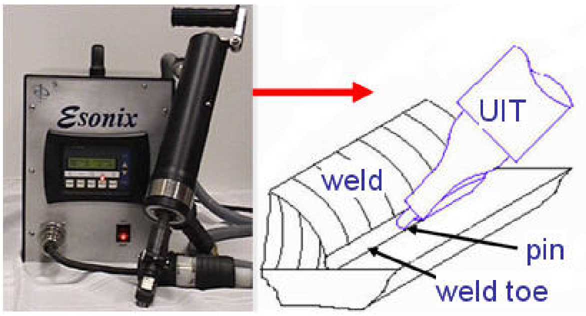

Figure 17: Ultrasonic Impact Treatment (UIT)

Several fatigue tests were carried out at the Institute for Steel Construction of Leibniz University Hannover with welded joints in as-welded and treated conditions. For example the Fig. 18 shows a comparison for Y-joints [12]. The S-N curve of the joints with UIT shows a significant increase in fatigue resistance compared to as welded joints. The as welded joints can be classified in FAT 90. This result corresponds with recommendations for tubular joints according to offshore-guidelines based on the hot-spot-concept. With a stress range of $\Delta\sigma_c = 204.5$ MPa for 2 million cycles the fatigue strength after post weld treatment by UIT was doubled compared to as-welded ($\Delta\sigma_c = 95.5$ MPa). The slope of the as-welded joints was m = 3.47. But for the second test series with UIT the slope was with m = 7.63 significantly higher.

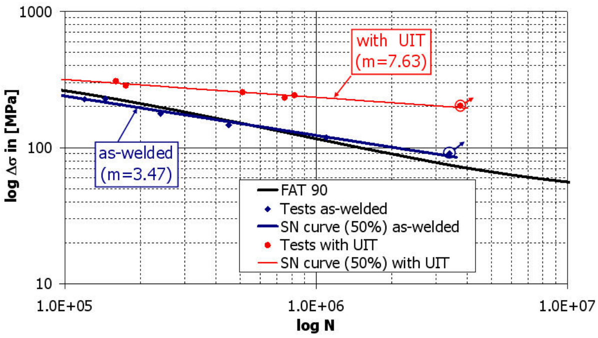

Figure 18: S-N-curves for as-welded and treated series

If a suitable method of post weld treatment like the presented high frequency hammer peening can be integrated in the fabrication (welding) process a significant increase in fatigue strength is possible for steel shells. In this way the fatigue design for sandwich tower sections could be realistic with the high strength steel S460 but not for S690.

6 Connections

The development of new sandwich and hybrid towers offers also the chance for new types of connections. In this paper a new kind of grouted connection is suggested by the authors, which will be especially developed for sandwich tower sections. The innovation of the new joint technique, presented in Fig. 19, is the double shear function as tube-in-tube connection.

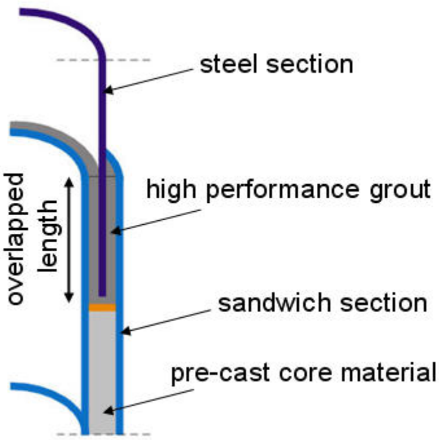

Figure 19: A new type of connection for tower sections

The upper steel section in Fig. 19 (s. also Fig. 3) is positioned between the inner and outer steel face of the sandwich section. After the vertical balance is ensured with jacks the gap can be filled with a high performance grout as used for grouted joints of monopiles. But in contrast to this the new kind of joint works as a double shear connection. Therefore, the overlapped length can probably be reduced in comparison to a conventional grouted joint. Furthermore, no ring flanges and no bolts are necessary to transfer the forces and moments. All advantages and disadvantages of the new joint compared to a bolted ring flange connection are summarized as follow:

Advantages:
- double shear tube-in-tube connection
- lower overlapped length as for grouted joints
- no eccentricities
- compensation of imperfection possible
- no ring flanges
- no bolts
- stiff connection due to three parallel shells
- lower costs for inspection and maintenance
- fewer hot spots than for ring flanges and bolts (fatigue)

Disadvantages:
- welding of shear keys in overlapped range
- additional steel shell for overlapped length
- more erection techniques and work

However, the same type of connection can be used between a sandwich section and a foundation section (s. Fig. 20).

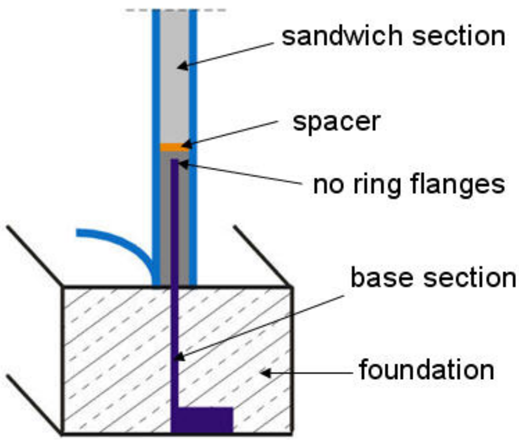

Figure 20: A new joint technique

The new joint technique for the foundation of sandwich towers is able to compensate vertical misalignments and imperfections. The foundation basket can be manufactured as usually for steel towers. All in all four ring flanges and the bolts for them can be saved when a sandwich shell is alternatively used for the first tower section. These savings in costs and materials will help to make the new sandwich tower concept more economical and competitive to the conventional tower concepts.

7 Conclusions

Alternatively to a steel tower section for WEC a sandwich tower section was analyzed with regard to the stability, fatigue and connections. 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. Within this test series sandwich cylinders were analyzed against shell buckling due to axial compression and compared to monocoque steel cylinders. The test series showed a significant increase in buckling load capacity for the sandwich cylinders, 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.

In addition the fatigue limit state was analysed to estimate the fatigue class, which would be necessary for sandwich section with high strength steels. For a sandwich section with S690 and comparable economical shell thicknesses the stress ranges would be too high for any fatigue class. Thus, the S690 is cancelled for this new tower concept. However, for a sandwich shell with S460 the fatigue design could be possible when methods of post weld treatment are used in the fabrication phase to increase the fatigue resistance of the welded joints between the shell elements.

Finally a new type of grouted joint was presented to connect a sandwich section with an upper steel section and also for connecting to the foundation. The new type is a double shear tube-in-tube connection without any ring flanges and bolts. Thus, the sandwich shells in combination with high-strength steels and the new joint techniques could be offered a new alternative solution for tower sections of WEC.

ACKNOWLEDGEMENTS

The authors would like to thank the German companies BRUGG Rohrsysteme GmbH, Elastogran GmbH, Pagel Spezialbeton GmbH as well as Sika Deutschland GmbH for the test specimen and core materials. Further thanks should also be given to SIAG AG which manufactured the test setup. In addition the authors would like to acknowledge for the financial support of the project GROW (grout structures for OWEC) provided by the German Federal Ministry for the Environment, Nature Conversation and Nuclear Safety. The authors are also grateful to the Institute of Building Materials and Institute of Materials Science of the Leibniz University Hannover for material tests on the steel and core materials.

References

[1] DIN 18800-4 (1990): Stahlbauten - Stabilitätsfälle, Schalenbeulen, *NABau im DIN e.V.*, Beuth-Verlag.

[2] DIN 18800-5 (1990): Verbundtragwerke aus Stahl und Beton - Bemessung und Konstruktion, *NABau im DIN e.V.*, Beuth-Verlag.

[3] DIN EN 1993-1-6 (2007): Bemessung und Konstruktion von Stahlbauten – Teil 1-6: Festigkeit und Stabilität von Schalen, *Eurocode 3*, Beuth Verlag.

[4] EN 10025-2 (2004): Warmgewalzte Erzeugnisse aus Baustählen, *Techn. Lieferbedingungen für unlegierte Baustähle*, CEN.

[5] Kapania, R. K. (1989): A review on the

analysis of laminated shells, *J. Pressure Vessel Technology*, Vol. 111, pp 88-96.

[6] Knorr, H. M. (2007): Experimentelle und numerische Untersuchungen zur Schalenstabilität von Sandwichzylindern, Diploma thesis, Institute for Steel Construction, Leibniz University Hannover.

[7] Lam, K. Y. and Loy, C. T. (1998): Influence of boundary conditions for a thin laminated rotating cylindrical shell, *Elsevier Composite Structures*, Vol. 41, pp 215 228.

[8] Schaumann, P.; Keindorf, C.; Matuschek, J. and Stihl, T. (2006): Schalenbeulen von Sandwichzylindern mit einem neuen Elastomer als Verbundwerkstoff, *Stahlbau*, Vol. 75, No 9, pp 748 753.

[9] Vinson, J. R. (1993): The behaviour of shells composed of isotropic and composite materials, University of Delaware, USA, Kluwer Academic Publishers.

[10] Zenkert, D. (1997): An introduction to sandwich construction, Warley, West Midlands, Engineering Materials Advisory Services, Ltd.

[11] International Institute for Welding (2007): Recommendations for fatigue design of welded joints and components, IIW document XIII-215r1-07

[12] Schaumann, P.; Keindorf, C. (2007): Enhancing fatigue strength by ultrasonic impact treatment for welded joints of offshore structures, ICSCS, 3rd International Conference on Steel and Composite Structures, S. 921-926, Manchester, UK

[13] Schaumann, P.; Keindorf, C.; Mickley, M. (2007): Fatigue assessment of welded joints considering residual stresses due to welding process and post weld treatment, International Conference on Fatigue Design, CETIM, Senlis, France