NEW CONNECTIONS FOR SANDWICH TOWERS OF WIND ENERGY CONVERTERS

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Summary

A new kind of tube-in-tube connection is presented which can be used to connect sandwich tower sections with steel sections without any bolts or ring flanges. Therefore, the upper steel section is positioned between the inner and outer steel face of the sandwich section. Thus, forces and moments can be transferred with shear stresses along an overlap length. The sandwich joint works as a double shear connection and can compensate vertical misalignments and imperfections. The ultimate limit state can be increased with prefabricated shear keys along the overlap length. In combination with the advantages of the new sandwich sections and the use of high-strength steels the presented tower concept could be a new alternative solution for WEC.

1. Introduction

The structural design of sandwich tower section for wind energy converters (WEC) has already been presented in [1]. The new kind of a tower section consists of two steel shells which are bonded together with a core material (s. Fig. 1). Compared to a steel tower section the shell thickness is splitted into 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.

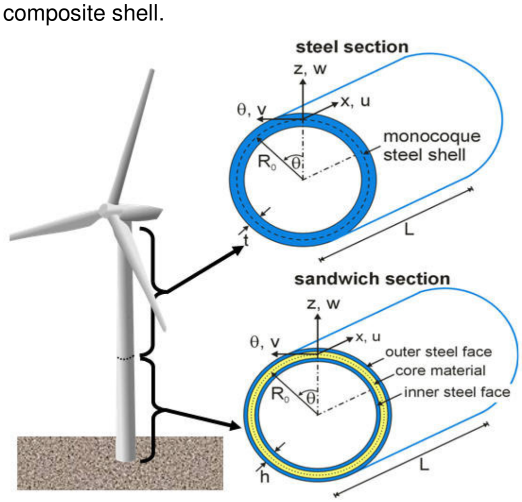

Fig. 1 A new tower concept for WEC

Different shell theories were used to estimate the stability of such double skin shell constructions [2]. A model scale test series with sandwich cylinders was carried out to analyse the shell buckling and the influence of different core materials [3]. Within a numerical pre-design the use of high strength steels for the inner and outer steel face was also considered to compare various types of tower configurations. The objective was to find the best combination of steel faces with a core material in the ultimate limit state. However, the fatigue limit state must also be considered [4]. The next challenge was to develop a new type of connection for such sandwich towers.

2. A new connection for tower sections

Especially for sandwich tower sections the authors suggest a new kind of connection presented in Fig. 2. The innovation of this joint is that it works as a double shear tube-in-tube connection.

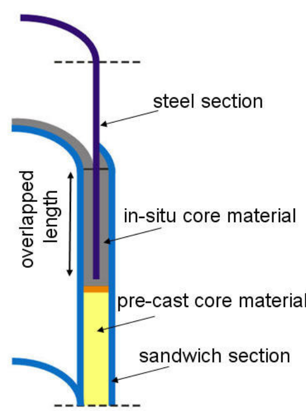

Fig. 2 A new connection for tower sections

The upper steel section in Fig. 2 is positioned between the inner and outer steel face of the sandwich section. After the vertical balance is ensured with jacks the gap along the overlap length can be filled with a core material. The new sandwich joint technique is able to compensate vertical misalignments and imperfections. Furthermore, no ring flanges and no bolts are necessary to transfer the forces and moments from the upper steel section to the sandwich section.

3. Details of the sandwich joint

In contrast to the well known grouted joint [6] which works as a single shear connection the sandwich joint belongs to the category of double shear connections (s. Fig. 3). Thus, the new sandwich joint can transfer the doubled force (F) for the same overlap length ($L_G = L_S$) compared to grouted joints. Alternatively the overlap length can be reduced for the same design load. But the towers of WEC are mainly loaded by bending moments. In addition to the normal force the bending moment must be transferred. Therefore, the overlapped length must be long enough for fixed conditions of the joint.

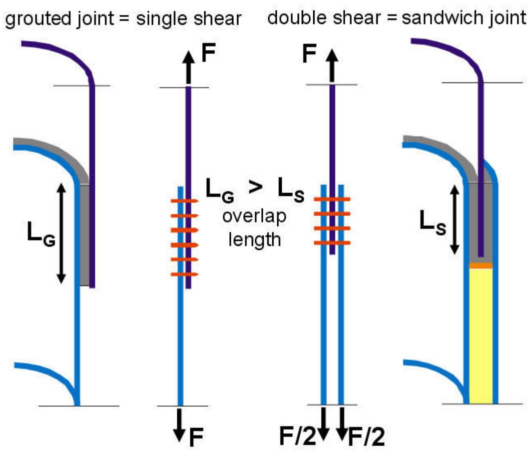

Fig. 3 Single and double shear connections

Compared to the bolted ring flange connection the new sandwich joint for tower sections has the following advantages and disadvantages:

Advantages:

- load transfer without eccentricities
- no ring flanges
- no bolts
- fewer hot spots than for ring flanges and bolts (fatigue)
- compensation of imperfections
- correction of vertical misalignments
- stiff connection due to three parallel shells
- lower costs for inspection and maintenance

Disadvantages:

- welding of additional shear keys
- more erection techniques and work during installation

For the installation of sandwich joints some more erection techniques like centralizer, consoles and jacks are necessary. But these components are well known from the installation of grouted joints. Furthermore, the injection process with pumps will not be new for the manufactures and installation companies.

4. Experimental investigation

A test series was carried out at the Institute for Steel Construction of Leibniz Universität Hannover to estimate the ultimate limit state of single shear connections. Therefore, two kinds of test specimens were used. The geometry of them is presented in Fig. 4. The first test specimen called is without shear keys (like ribs) and has smooth interfaces between the steel tubes and the core material. The second one is with shear keys at the surfaces of the steel areas which are in contact with the core material. The shear keys with regular geometry and distances should increase the frictional resistance. The local behaviour at the interface between steel and core is similar for single and double shear connections but the maximum bearing capacity would be higher for double shear connections.

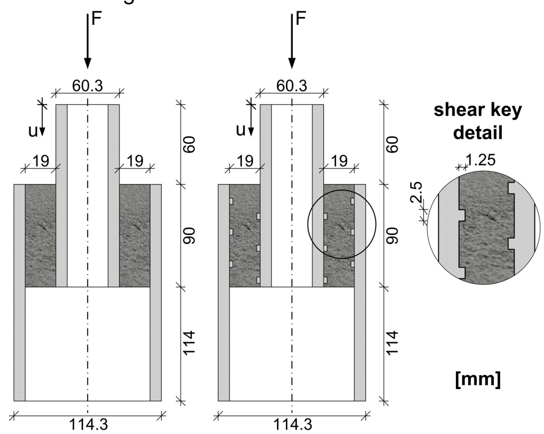

Fig. 4 Geometry of test specimens without (left) and with shear keys (right)

The experimental setup with the test specimen is presented in Fig. 5.

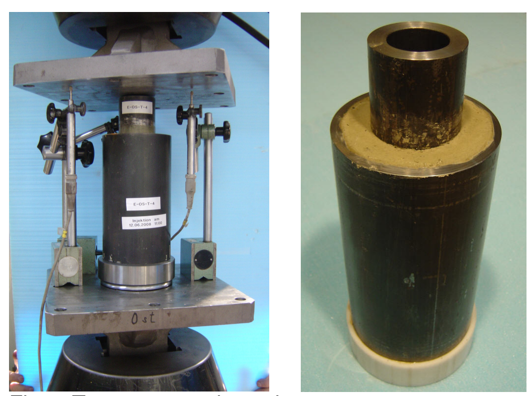

Fig. 5 Test setup and specimen

During the test specimens were injected with core materials an adapter ensured the vertical orientation of the inner and outer steel tube. After the injection process was finished the test specimen was positioned in the test machine including load cell and displacement transducers around the circumference. All test specimens were loaded by an axial compressive force and tests were carried out displacement controlled.

In Fig. 6 the force-displacement curves are presented for the test specimen without shear keys. The test specimen E-OS-T-4-1 has with 150 kN the highest ultimate limit state because it has the highest bonding strength of all core materials. After the bonding was broken at the interfaces shear sliding begins between the inner and outer tubes but without a significant decrease in bearing capacity.

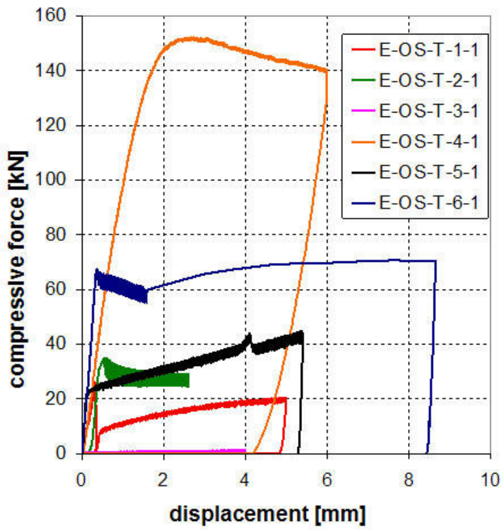

Fig. 6 Ultimate limit states for different core materials without shear keys

The test results with shear keys are also presented as force-displacement-curves in Fig. 7. In contrast to the test series without shear keys the core materials with lower bonding strength have higher ultimate states. In these cases the compressive strength of the core materials and the frictional resistance of the shear keys are more important as the bonding strength of the core materials.

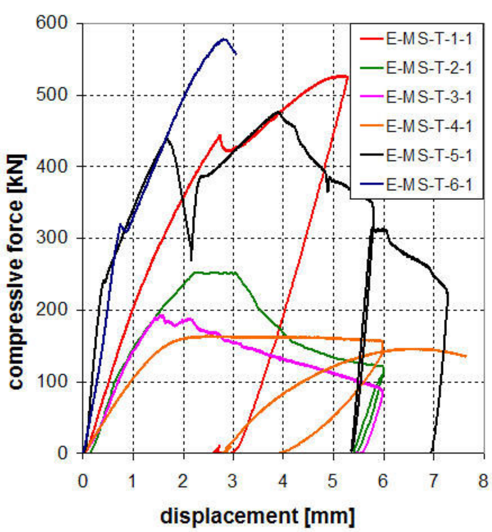

Fig. 7 Ultimate limit states for different core materials with shear keys

The test specimen E-MS-T-6-1 has with 580 kN the highest axial load capacity. But the first crack was already observed by 310 kN with a decrease in stiffness. The reason for that is a local damage at the highest stressed shear key. However, the ultimate limit state of single and double shear connections can be increased with shear keys.
In contrast to this the shear keys have no positive influence by the test specimen E-MS-T-4-1. The ultimate limit state is with 160 kN similar to the result for E-OS-T-4-1 because the compressive strength is too low. Thus, the optimized core for a shear connection with shear keys should be a stiff and injectable material with high compressive strength. For smooth interfaces without shear keys the bonding strength of the core must be sufficient.

5. Failure modes

After testing the local bond behaviour and the failure modes of such shear connections were analyzed in [5]. Therefore, some test specimens were cut longitudinally to evaluate the interfaces between the steel tubes and the core materials. The observed cracks from one test specimen with shear keys were presented schematically in Fig. 8. These cracks were located between the shear keys from the inner tube which developed to the shear keys at the outer steel tube (s. Fig 8 left).

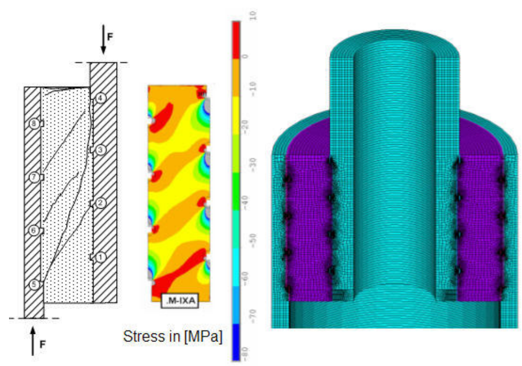

Fig. 8 Cracks in core materials and stress concentration in numerical models [5]

In addition to the experimental investigations a numerical model (s. Fig 8 right) was developed in [6]. With this FE-model numerical simulations were carried out to study the stress concentrations inside the core and at the interfaces. The FE-plot in Fig. 8 (middle) shows in red colour the tension stresses in the core material. The location and the direction of these diagonal tension zones confirm very well with the observed cracks. The local zones below and above the shear keys are highly compressed.
In the ongoing research project “GROW” large model scale tests for single shear connections are planned with different core materials to estimate the influence of the core material properties in ultimate and fatigue limit states. The details of the test setup and the test specimens were already published in [6] and [7].

Finally the following failure modes can be occurred when single or double shear connections are loaded with axial forces up to the ultimate limit state. The most important failure mode for shear connections without shear keys is plotted in Fig. 9 (left). If the bonding strength of the core material is exceeded the steel tubes begin to slide parallel to each other.
In contrast to this the failure modes for connections with shear keys is completely different. Depending on the geometry and the distance of the shear keys three modes are possible which are plotted in Fig. 9 (right). If the distance between the inner and outer shear keys is too long single shear keys will be damaged. On the other hand if distance is too short the crack will occur vertically along one row of shear keys. Thus, the distance is optimized when the shear keys can transmit compressive stresses from the inner to the outer interface.

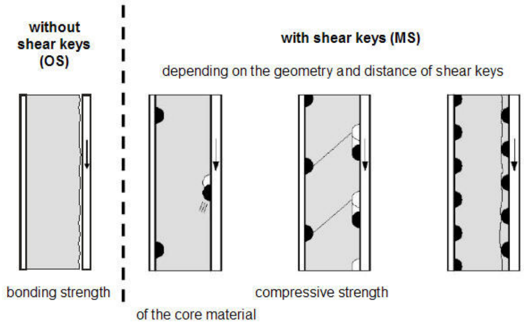

Fig. 9 Failure modes in single shear connections with and without shear keys

For the new tower concept with sandwich constructions the application with shear keys is recommended especially for the connection zone (sandwich joint). But for the section zone below the sandwich joint (sandwich cylinder, s. Fig. 1) the application without shear keys is recommended because only a minimum of load transfer from one shell to the other is necessary. Therefore, the lower interface stresses can be transmitted if the bonding strength is sufficient of the chosen core material.

6. Conclusions

A new tower concept with a sandwich section was analyzed with regard to shell stability. The sandwich shell consisted of an inner and outer steel face, which were bonded adhesively to different core materials between them. For a combination with upper steel section a new kind of tube-in-tube connection was presented. Therefore the upper steel section is positioned between the inner and outer steel face of the sandwich section. Thus, the sandwich joint works as a double shear connection and can compensate vertical misalignments and imperfections. Furthermore, no ring flanges and no bolts are necessary to transfer the forces and moments between the sections. The ultimate limit state of the sandwich joint depends on the compressive and bonding strength of the core material and can be increased with shear keys along the overlapped length.

7. Outlook

The next research phase contains experimental investigation with dynamic loads to analyze the fatigue behaviour of the different core materials with and without shear keys. Furthermore, the configuration of double shear should be compared with single shear connections. The goal is to find the best configuration of bonding and compressive strength for the core materials to enhance the ultimate and fatigue limit state for the connection and section area. Thus, the sandwich tower concept in combination with high-strength steels and the new joint technique could be offered a new alternative solution for WEC.

8. Acknowledgements

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9. References

[1] Schaumann, P.; Keindorf, C.: Structural Design of Hybrid-Towers for Wind Energy Converters, EWEC, Conference Proceedings, Brussels, Belgium, 2008
[2] Schaumann, P.; Keindorf, C.; Knorr, H.M.: Zur Schalenstabilität von Sandwichzylindern – Theorie, Bauingenieur, Band 83, Heft Juni, Springer Verlag, 2008
[3] Schaumann, P.; Keindorf, C.; Knorr, H.M.: Zur Schalenstabilität von Sandwichzylindern – Experiment, Bauingenieur, Band 83, Heft August, Springer Verlag, 2008
[4] Schaumann, P.; Keindorf, C.: Hybrid-towers for offshore wind energy converters, ISOPE, Proceedings of 18th International Offshore and Polar Conference, Volume 1, Vancouver, Canada, 2008
[5] Niebuhr, L.: Experimentelle und numerische Untersuchungen zum Normalkrafttragverhalten von hybriden Verbindungen, Diploma Thesis, Institute for Steel Construction, Leibniz Universität Hannover, 2005
[6] Schaumann, P.; Wilke, F.; Lochte-Holtgreven, S.: Nonlinear Structural Dynamics of Offshore Wind Energy Converters with Grouted Transition Piece, EWEC, Conference Proceedings, Brussels, Belgium, 2008
[7] Schaumann, P.; Wilke, F.; Lochte-Holtgreven, S.: Grout-Verbindungen von Monopile-Gründungsstrukturen - Trag- und Ermüdungsverhalten, Stahlbau 77, No 9, 2008