ce/papers
The online collection for conference papers in civil engineering
Ernst & Sohn
A Wiley Brand

NORDIC STEEL 2019
The 14th Nordic Steel Construction Conference,
September 18–20, 2019, Copenhagen, Denmark

Shell Structures Made of Curved Sandwich Panels

Assessment of the Load-Bearing Capacity

Sören Grimm*[,a], Jörg Lange[a]

[a]Technische Universität Darmstadt, Institute for Steel Construction and Materials Mechanics, Germany
grimm@stahlbau.tu-darmstadt.de

ABSTRACT

Lightweight constructions made of sandwich panels became well established for roof and wall claddings of industrial structures. Due to their good heat insulation, their excellent weight to load ratio and high load-bearing capacity as well as the economical manufacturing and erection process, sandwich structures are build frequently. Besides the mentioned advantages the linear manufacturing process of sandwich panels usually limits the possible building cubature to rectangular shapes. In an interdisciplinary project, architectural, civil engineering and mechanical engineering institutes of Technische Universität Darmstadt are working on a design concept building shell structures with linear manufactured curved sandwich panels.
A preliminary study indicates that arched sandwich beams have a high potential regarding the load-bearing capacity. The comparison between arched and single span sandwich beams shows that, even for asymmetric loads, resulting stresses in the two-hinged arches are significantly lower than in the related simply supported single span beams.
To verify the results of the numeric study full-scale tests on curved sandwich panels will be performed. Furthermore, an assessment of the load-bearing behavior of the panels joints loaded with axial forces is planned. Based on the results further numeric studies will be conducted to investigate the behavior of whole shell structures following the developed design principle by taking into account realistic load cases for exemplary building applications, giving special attention to asymmetrical loads.
Moreover, further research regarding the requirements for supporting structures as well as for the connection between the shell structure and the supporting structure is necessary to take into account the high axial forces, which are not common in sandwich structures.

Keywords: Shell Structures, Sandwich Panels, Curved, Lightweight

1 INTRODUCTION

Lightweight steel constructions made of sandwich panels became well established for roof and wall claddings of industrial structures. Commonly these panels are composed of a thick core layer (40 mm to 300 mm) with a low density and two thin (0.4 mm to 1.0 mm) metal face sheets. Due to their good heat insulation, their excellent weight to load ratio and high load-bearing capacity as well as the economical manufacturing and erection process, sandwich constructions are build frequently. Besides the mentioned advantages the linear manufacturing process of sandwich panels usually limits the possible building cubature to rectangular shapes.
Another construction type coming with an even lower ratio of weight to load are shell structures. In the 20th century, many of these structures were built, following the technical and scientific progress of that time. Disadvantages of most realized structures were that large and unique temporary constructions as well as large installation expense were necessary. In times of growing importance of construction time, the growing costs of construction site equipment and wages, building an economical efficient structure requires high levels of prefabrication and short assembly times.

In an interdisciplinary project, architectural, civil engineering and mechanical engineering institutes of the Technische Universität Darmstadt are working on combining the advantages of these two types of design. The research is aimed on the development of a concept to build shell structures out of linear manufactured curved sandwich panels with a variable width. This paper focuses on presenting the work status of the Institute for Steel Construction and Materials Mechanics, which consists of the assessment on the load-bearing capacities of these structures.

2 STATE OF THE ART

In 1970 Otto Jungbluth presented the first lightweight shell structure made of sandwich panels (1). His dome has a span of 45 m and consist of 120 sandwich panels. Each panel is uniaxially curved, has a variable width und was produced by Hoesch AG in single item fabrication.

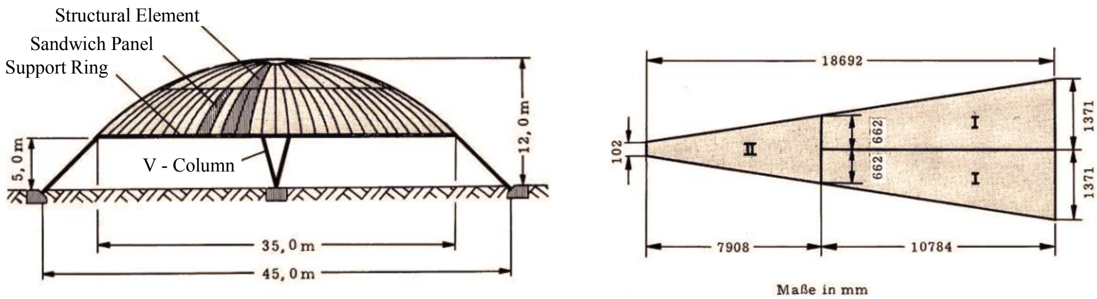

Fig. 1. a) Dome by O. Jungbluth; b) Structural Element (1)

The panels with a length of approx. 8 m or 11 m are approx. 0.1 m to 1.4 m wide (see Fig. 1) and have a depth of 150 mm. The polyurethane foam core connects two metal face sheets with a thickness of 1 mm. The structure is joined by pop rivets and bolted connections, which causes large expense of installation as well as high local stresses in the face sheets.

On the site, 40 structural elements were merged to a shell structure (see Fig. 1), assembled by three sandwich panels, each. The joint of the structural elements as well as the joint of the sandwich panels of each structural element itself had to be foamed after connecting the face sheets with the mentioned fasteners in situ.

After several reconstruction works, which certainly did not affect the main structure, today the dome is the Information Centre of Hannover Fairs. Taking into account that, according to the German code (2), facilities have to be designed to operate up to 50 years, it can be concluded that the dome is a permanent lightweight shell structure with viable performance efficiency. However, despite its high performance structures like the dome of Otto Jungbluth can hardly be built economically, considering todays boundary conditions.

Nevertheless in 2010 Klaus Berner reported about established hall structures built with a roof structure made of linear manufactured uniaxially curved sandwich panels in Italy (3). In this context, he also reminded of the structural potential of arched structures, which let assume a larger span of a curved panel with two hinged supports.

3 ASPIRED DESIGN PRINCIPLE

This research work is aiming on solutions realizing shell structures using linearly manufactured curved sandwich panels with plane face sheets and a polyurethane core taking advantage of their high load-bearing capacity and high level of prefabrication. To manage the design process a design tool is developed, which is able to determine the geometry of each panel and provide the data for the production process as well as the load-bearing analyses. Furthermore, a roll-forming process of the face sheets is under examination implementing geometric data determined in the design tool. In addition, the load-bearing performance of these structures will be analysed to work out application guidelines regarding realistic span and curvature radii of these structures.

A detailed report on the design process and the development of the design tool can be found in (4). Fig. 2 shows an exemplary paneling process of a spherical surface by extruding curved planes from intersection lines between the surface and a section plane and the following subsequent intersection of the adjoined curved planes.

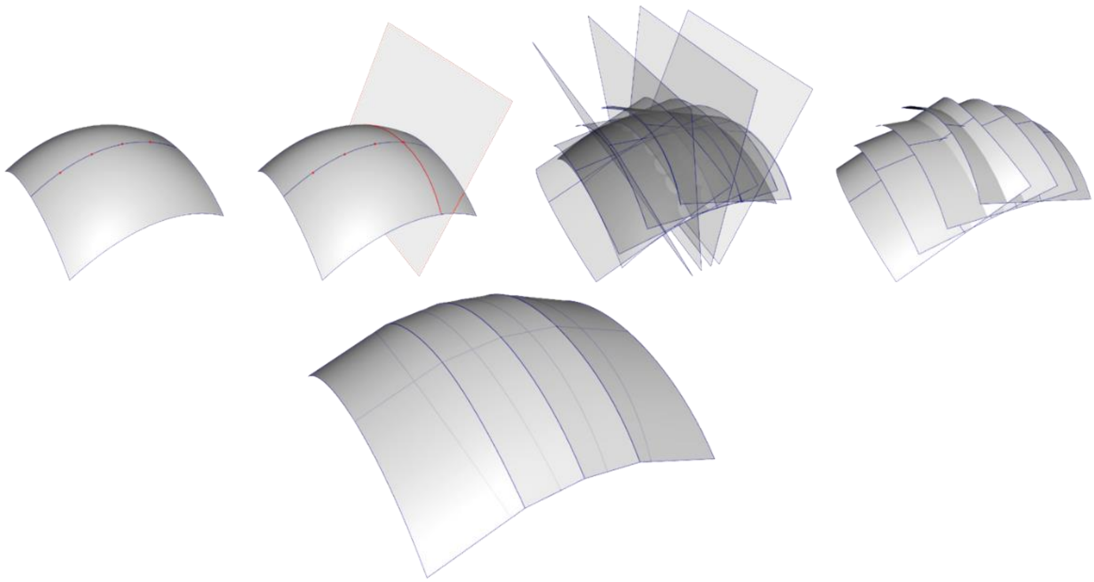

Fig. 2. Work Steps of an Exemplary Paneling Process (4)

In the example the panels are curved along the longitudinal direction, and in transverse direction, the curvature is approximated by a polygon. This design principle requires that the sandwich panels are produced with variable width as well as inclined joint planes. All features of the panels can be pre-engineered in computer models.
In a first step, the characteristics of the developed structure can be compared to the rough applications guidelines from production process as well as the preliminary investigations on the load-bearing capacities immediately. Following the geometry of the panels can be reviewed in detail regarding the boundary conditions of the production process. In addition the load-bearing capacity of the structure has to be examined in an accurate static model taking into account the load cases prescribed by the current design standards.
The design tool will be able to consolidate the results of the manufacturing review as well as the static analyses. Thus an integral design process is developed, which allows a close cooperation between architectural design, structural engineering and the manufacturer.

4 LOAD-BEARING CAPACITY

At this time preliminary investigations on the load-bearing capacity of two-hinged sandwich arches indicate their high structural potential compared to single span sandwich beams. Because the load bearing behavior of the joint was just analysed regarding lateral forces so far, for example in (5), the study is based on the load bearing behavior in longitudinal direction of the panels.The load-bearing capacity of these two kinds of structure was determined by loading them with the same unit load cases. Single span as well as arched sandwich beams with different ratios of curvature have been loaded over their entire length respectively over half of their length. They were analysed in two-dimensional numerical models using the finite element method. Following up the modelling of the arched sandwich beam is described in detail.

4.1 Finite Element Modelling

The structures are analysed in two-dimensional numerical models with a constant width of 1 m. The supports of the two-hinged arches where modelled by rigid beam elements connecting the two face sheets of the sandwich cross section similar to an end-plate connection (see Fig. 3 and 4). The end-plates themselves were simply supported in the centroid of the sandwich cross section (see Fig. 4).

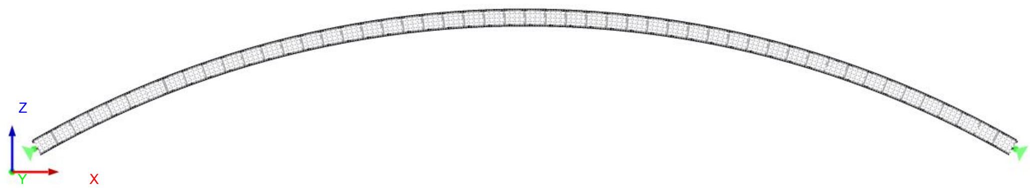

Fig. 3. 2D Finite Element Model

The steel face sheets of the sandwich panels were modelled with curved beam elements using a common ideal-elastically isometric material with a Young's modulus of 210,000 N/mm² and a Poisson's ratio of 0.3. The core of the sandwich panel was modelled using shell elements. Deviating from the face sheets the core material was modelled using an ideal-elastically orthotropic material law. Therefore, it was possible to take into account a realistic Young's modulus and shear modulus of the core material. The shear modulus of the core was defined within a range of 2.5 N/mm² to 4.0 N/mm². Giving regard to the fact that the Young's modulus of the core material has a minor influence on the structural behaviour of the sandwich arches, it was set to the same value as the shear modulus. According to (6) the Poisson's ratios of all directions were set to 0.25.

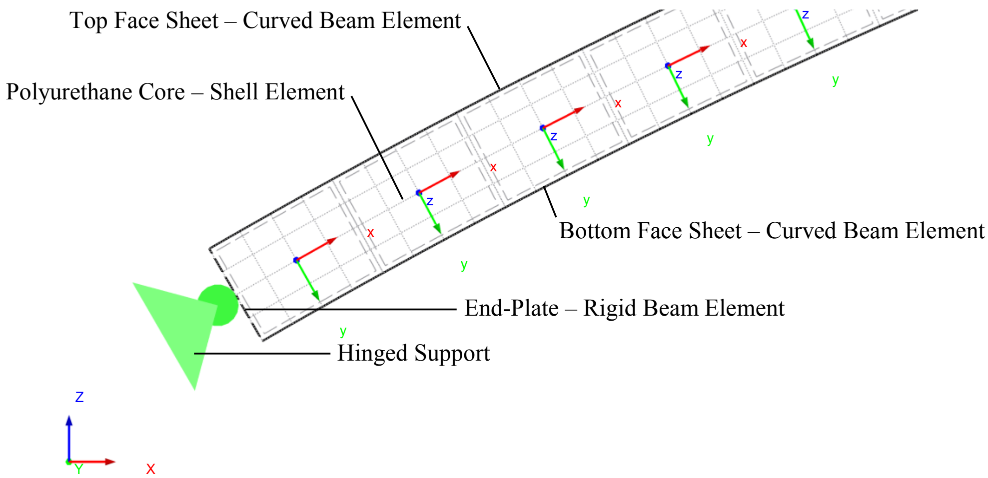

Fig. 4. 2D Finite Element Model – Detail at Support

Since the properties of core materials are usually determined vertical to the axis of panel, the plane of the core is modelled by trapezoidal shell elements, which approximate the curved form like a polygon. According to (7) the limit value for the length of these elements are determined as twice the depth of the sandwich panel. The axis of each shell element is aligned with the longitudinal axis of the sandwich panel at the associated location. The axis and the mesh of these shell elements can be seen in Fig. 4.
All structures were analysed by the theory of large deformations. Based on the modelling global and local stability failure modes like buckling and wrinkling are implemented in the numerical models.

4.2 Assessment on a Rough Scope of Application

To determine a rough scope of application as well as the potential of load-bearing capacity a numerical parameter study was conducted. Structures with a span of 2 m to 30 m and a ratio of curvature radius to span from 0.5 to 30.0 were analysed. The examined sandwich panels had depth of 40 mm to 300 mm and both face sheets were 0.50 mm thick minus a common zinc coating of 0.04 mm. All structures were loaded by a projected line load of 1 kN/m to make sure that the bearing stresses result from the same total load. Table 1 shows the examined parameters.

Table 1. Examined Parameter of the Numerical Study

Span in m	2	4	6	8	10	12	16	20	24	30		
Radius/Span	0.50	0.60	0.70	0.75	0.80	0.90	1	2	4	8	16	30
Thickness in mm	40	80	120	160	200	240	300					

To determine a rough scope of application regarding the span Fig. 5 shows the percentage of stable models of each span for all symmetric and asymmetric loaded two-hinged arches. A model is unstable if it fails by global or local instabilities. It is important to note that no safety factor is included in the results. Furthermore it should be mentioned that the eigenvalue analyses of selected models show that the wrinkling stress according to Stamm & Witte (8) is modelled quite accurate.

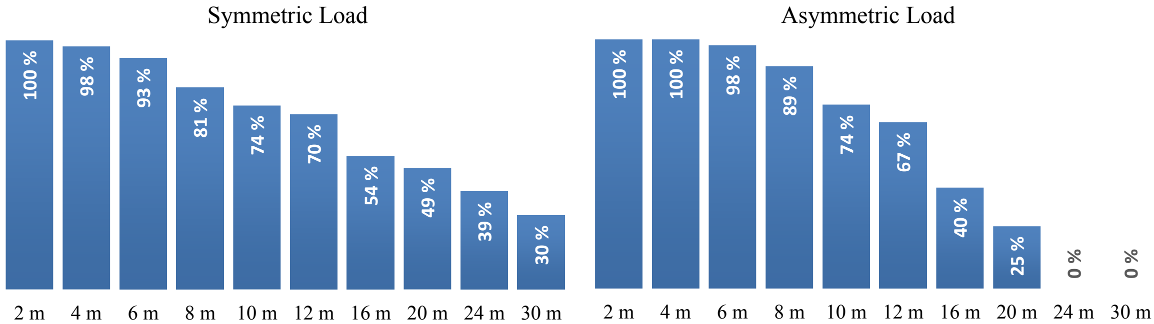

Fig. 5. Percentage of Stable Symmetric and Asymmetric Loaded Sandwich Arch Models vs. Span

Taking into account, that a load of 1 kN/m is a usual design snow load in large parts of Germany, nevertheless a rough scope of application can be derived from the results of the study. Furthermore, Fig. 5 shows that the two-hinged arches are very sensitive to asymmetric loading. Although the structure is loaded by only half of the total load compared to the symmetric load cases the percentage of the stable models strongly decreases starting from a span of 12 m.

A closer look on the detailed results of the study reveals that most models up to a span of 12 m show good load-bearing performance, panels with a depth of only 40 mm and models with large ratios of curvature $R/S \geq 8$ excepted. Therefore, a span of $l \leq 12$ m, a panel thickness of $D \geq 80$ mm and a ratio of curvature of $R/S \leq 4$ are proposed as rough boundaries of application. Structures beyond these boundaries may also be realised depending on the panels depth and the thickness of the face sheets as well as its ratio of curvature and have to be analysed in detail for each individual case.

4.3 Potential of Load-Bearing Capacities

To compare the load-bearing capacities, the normal stresses in the face sheets of the two-hinged arches and in the simply supported single span beams, resulting from the corresponding load cases, have been determined. They were compared to the yield stresses of usual face sheet material, as well as the wrinkling stress of the modelled sandwich cross section. The wrinkling stress of 89.8 N/mm² was calculated by using equation 8.50 in Stamm & Witte (8). Furthermore, the load capacity resulting from a representative shear strength in accordance to the defined shear modulus was taken into account.

Table 2 shows some exemplary results of the maximum normal stresses in the face sheet as well as maximum vertical deflections for panel depth of 300 mm and a span of 10 m under symmetric load of 1 kN/m.

Table 2. Maximum Value of Normal Stresses (Compression) in the Face Sheet

Structure Type	Single Span	Arch											
Radius/Span	-	0.50	0.60	0.70	0.75	0.80	0.90	1	2	4	8	16	30
Normal Stress in N/mm²	90.6	14.7	8.1	7.8	7.9	8.0	8.6	9.5	20.4	41.4	65.4	71.3	65.2
Max. Deflection in mm	46.6	3.8	1.0	0.7	0.7	0.6	0.6	0.7	1.9	6.2	14.5	20.9	22.7

The comparison in table 2 shows that, for a large range of curvature ratio, the load-bearing stresses as well as the deflections of the exemplary two-hinged arches are significantly lower than in the related simply supported single span beam. The knowledge regarding the advantageous curvature ratios is transferable to other constellations of parameters. The presented results further show that the proposed scope of application is just a rough estimate of the possible range. With sandwich panels of large depth, thick face sheets and optimal curvature ratio even large spans seem possible.

5 CONCLUSIONS AND OUTLOOK

In a current project three institutes of Technische Universität Darmstadt developed a new design principle to build shell structures using economically manufactured sandwich panels with a high level of prefabrication. A preliminary study shows that arched sandwich beams have a high potential regarding the load-bearing capacity. Comparisons between arched and a single span sandwich beams show that, even for asymmetric load, resulting bearing stresses in the arched beam are significantly lower than in a related single span beam.

In the course of the project it is planned to produce curved sandwich panels and verify the results of the numeric models with full-scale tests. Furthermore, an assessment on the load-bearing behavior of the panels joints loaded with axial forces is planned. Based on the results further numeric studies will be conducted to investigate the behavior of whole shell structure following the developed design principle also taking into account realistic load cases for exemplary building applications giving special attention to asymmetrical loads.

Moreover further research regarding the requirements for supporting structures as well as for the connection between the shell structure and the supporting structure is necessary to take into account the high axial forces which are not common in sandwich structures.

ACKNOWLEDGEMENT

The Institute for Steel Construction and Materials Mechanics would like to thank the German Federation of Industrial Research Associations (AiF) and the Research Association for Steel Application (FOSTA).

REFERENCES

1. **Jungbluth, Otto.** Weitgespannte Sandwichkuppel im Werkstoffverbundsystem Stahlfeinblech - Polyurethanhartschaum. *IABSE congress report.* 1972.

2. **DIN Deutsches Institut für Normung e.V.** DIN EN 1990. *Grundlagen der Tragwerksplanung.* Berlin : Beuth Verlgag GmbH, 2010.

3. **Berner, Klaus.** Gekrümmte Sandwichpaneele. *Stahlbau 79.* 5, 2010.

4. **Reising, Jakob, Kehl, Marvin and Schäfer, Stefan.** A Design Tool for Shell Structures made of Curved Sandwich Panels. *Proceedings of the 1st Annual Design Research Conference (ADR18).* 2018.

5. **Böttcher, Marc.** *Wand - Sandwichelemente mit Öffnungen.* Darmstadt : Institut für Stahlbau und Werkstoffmechanik, 2005.

6. **Nelke, Harald.** *Tragfähigkeit von Sandwichelementen unter Biegung und Querdruck.* Darmstadt : Institut für Stahlbau und Werkstoffmechanik, 2018.

7. **Lange, Jörg and Berner, Klaus.** *Sandwichelemente im Hochbau.* Berlin : Ernst & Sohn, 2010. 978-3-433-02939-8.

8. **Stamm, Klaus and Witte, Horst.** *Sandwichkonstruktionen - Berechnung, Fertigung, Ausführung.* Wien : Springer-Verlag, 1974. 13:978-3-7091-8335-9.