Efficient construction of concrete shells by Pneumatic Forming of Hardened Concrete: Construction of a concrete shell bridge in Austria by inflation

Benjamin Kromoser1 | Johann Kollegger2

1Institute of Structural Engineering, University of Natural Resources and Life Sciences, Vienna, Austria
2Institute for Structural Engineering, TU Vienna, Vienna, Austria

Correspondence
Benjamin Kromoser, Institute of Structural Engineering, University of Natural Resources and Life Sciences, Vienna, Peter-Jordan-Straße 82, 1190 Vienna, Austria.
Email: benjamin.kromoser@boku.ac.at

Abstract
Concrete shells are very efficient structures, spanning wide areas with very little construction material. Unfortunately the formwork needed to erect concrete shells is still very labor and material intensive. An alternative construction method which is more time and resource friendly is Pneumatic Forming of Hardened Concrete. A simple air cushion in combination with additional post-tensioning tendons are used to transform a flat concrete plate into a double curved shell. This paper describes the design and construction of the first practical large-scale application of this building method for the construction of the deer pass “AM 2” over the newly built two-track rail Koralmbahn in Carinthia in the south of Austria. The plan measurements of the bridge are 36.2 m by 38.7 m with the height of the shell from the top edge of the foundations to the vertex mounting to 7.6 m. Within the construction process a flat 100 mm thick hardened concrete plate with a weight of 546 t was lifted to the designed double curved shell. This thin concrete shell served as lost formwork for the final bridge.

KEYWORDS
active bending of concrete, concrete shell, flexible formwork, pneumatic forming of hardened concrete, pneumatic formwork, pneumatic formworks in structural engineering, resource efficient structural engineering, shell bridge, structural engineering

1 | INTRODUCTION

The efficiency of concrete as a construction material is very much dependent on the structure itself. It can be increased by optimizing the form of the structure according to the applied loads. One of the best examples for a very effective form is the concrete shell. If the geometry is optimized shear and bending stresses can be avoided and the dead weight as well as further permanent loads can mainly be transferred by in-plane membrane forces. The result of such an optimization is in most cases a double curved geometry requiring a complex formwork and falsework in order to be produced. These formworks are currently custom-built wooden or steel structures. Single modules consist of closely positioned form lamellas which serve as a carrier for the formwork shell. For large structures an additional framework is required to support the modules. In most cases these produced shells are unique structures resulting in one or only a couple applications of the formwork...
modules. A great example of a concrete shell is the structure built in Chiasso, Switzerland using wooden formwork produced by use of computer numerical controlled production technologies.\(^1\)

A construction option for rotationally symmetric structures is to design formwork elements using ring tension or compression forces which transfer the loads of the fresh concrete to the foundations, considerably reducing the amount of required formwork.\(^2\) Furthermore several pneumatic formwork systems have been developed and tested in the past decades.\(^3\)–\(^10\) An extensive summary and analysis of the most important pneumatic formwork systems can be found in.\(^11\) Double curved formwork can also be produced by milling free formed structures out of solid blocks made for example out of polystyrene. A negative aspect of this option is the large amount of accumulated waste. Further alternatives are to mill forms out of wax that can be melted and reused\(^12,13\) or to mill forms out of frozen sand.\(^14\) Another possibility is to use flexible computer aided formwork to produce free formed small-scale precast elements and to assemble them to larger surfaces afterwards. A number of actuators make the formwork shell flexible and therefore making a fast adaptation of the geometry possible.

The maximal curvature is limited with this system due to geometric and physical constraints.\(^15\)

In order to erect large concrete shells with minimal effort, the authors invented a new shell construction method with the name Pneumatic Forming of Hardened Concrete (PFHC). The functionality will be explained subsequently.

## 2 PNEUMATIC FORMING OF HARDENED CONCRETE—PFHC

The idea of PFHC is to simplify the production of concrete shell structures by bending connected thin flat hardened concrete plates to a double curved shell structure. The flat hardened concrete plates are lifted by inflating an air cushion which is placed underneath and by tensioning post-tensioning tendons mounted at the circumference as shown in Figure 1. The core of the construction method is the “cold” bending process of concrete itself. The bending behavior as well as the suitability of different material combinations for this purpose were tested in extensive preliminary experiments. In detail, two series of bending tests, two series of burst tests with different pneu materials, joint
tension tests, bond tests and centric tensile tests were performed\textsuperscript{16–18} in the first development steps by the authors. The functionality of the complete construction method was tested in two large scale experiments. A spherical concrete shell with a diameter of 10.8 m and a height of 3.2 m and a free formed concrete shell with the plan measurements of 17.6 m by 10.8 m and a height of 2.9 m were erected as explained in.\textsuperscript{11} Both shells had a thickness of 50 mm. The full experimental program performed during the research project “Freiformflächen aus Beton” is shown in Figure 2 and explained in detail in the final report.\textsuperscript{20} With the feasibility of the PFHC proven, the next step was to apply the method to erect the first building structures.

The first client, who decided to apply PFHC for the construction of a concrete shell bridge, was the Austrian Railways Österreichische Bundesbahnen (ÖBB). The project team decided to introduce an intermediate construction step, a test shell in scale 1:2, meant as a “learning” structure for the constructing engineers and the construction company. The completed test structure, which serves as an event canopy, has the plan measurements of 26.5 m by 19.1 m, with a height of 4.2 m and a final thickness of 150 to 200 mm. The structure is described in\textsuperscript{21} in detail. The finished canopy is shown in Figure 3. The gathered knowledge during the construction of this test shell was used to further improve the construction technique and to optimize the design of the construction details. Subsequently the main structure, the shell bridge “AM 2” over the newly built two-rail track Koralmbahn, was built in 2017 and 2018. The plan measurements of the bridge are 36.2 m by 38.7 m. The height from the top edge to the vertex mounts to 7.6 m. The construction site is shown in Figure 4.

3 | FORM FINDING AND DESIGN

The design process of the shell bridge was split into four steps as shown in Figure 5. In the first step (1) the form of the final bridge was optimized according to the geometric, static, economic and procedural boundary conditions. In the second step (2) the bridge form was completed to a total cupola. Afterwards the smooth cupola was discretized into semi-discrete segments (single curved strips) (3) and unrolled (4) to form a flat plate.

3.1 | Determination of the final bridge shape (step 1)

The final shape of the complete shell for the shell bridge is mainly affected by three factors; first of all by the applied loads (dead weight of the shell and the vertical and horizontal forces from the earth covering), second of all by the minimization of the construction material needed and lastly by the procedural requirements from the PFHC-method. The complete optimization process is described in\textsuperscript{22} in detail. A particle-spring system was chosen as the basis for the form finding. The virtual model was loaded with the real acting forces and constraints, and the system was allowed to find its own equilibrium configuration.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Finished test structure serving as event canopy © Christoph Panzer}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Construction site of the test shell and the shell bridge “AM 2”}
\end{figure}
permanent loads (dead weight, horizontal, and vertical earth pressure) aimed in the opposite direction. Within a numerical calculation the elastic net was deformed until an equilibrium was found. The virtually applied loads are shown in Figure 6. The obtained shape was used as a basis for the bridge design. The final design is shown in Figure 7.

3.2 | Completion to a full cupola (step (2))

The tensile force in the membrane of the pneumatic formwork is directly linked to the radius of curvature. A large radius of curvature, as present for the large structures, results in a high tensile force in the membrane. This requires a full cover of the membrane by the concrete plate. Thus, the final bridge shape (Figure 5 (1)) has to be completed to a full cupola for the inflation process (Figure 5 (2)). For this purpose two steps had to be taken. First, the two bottom edges are connected to form a closed curve which is as continuous as possible. Discontinuities must be avoided, as they would cause stress peaks in the thin concrete structure. Secondly, the longitudinal section curve of the bridge is extended.

3.3 | Discretization and unrolling of the reference geometry (steps (3) and (4))

The fact that each segment of the flat concrete plate can only be bent in one direction requires discretization of the double-curved cupola into a sequence of developable surface strips. The software Evolute tools was used in the case of the presented project in combination with the Computer Aided Design program Rhinoceros. First, a coarse mesh is modeled that forms a very rough discrete representation of the reference geometry and determines the number of developable segments. These segments represent the basis of a grid in which the rows are refined gradually. After each refinement the resulting mesh is optimized. The planarity of each mesh face, expressed through the shortest distance between face diagonals, is the main criterion. The used algorithm implemented in the software Evolute tools tries to minimize the sum of the squared distances. If all distances are zero, the strips are perfectly developable. In order to keep the optimized geometry as close as possible to the reference geometry, several other criteria are considered. With the help of the assigned weights the user is able to determine the importance of the individual criteria and thus influence the outcome of the optimization. The process allows to find a geometry consisting of single curved strips that is very close to the smooth surface. Within the final design step this geometry is unrolled to a flat plate. In the case of the “AM2” shell bridge a perfect geometry for the production of the concrete plate weighting 80 tons for the construction of the test shell (thickness 50 mm) and 546 tons for the construction of the shell bridge (thickness 100 mm) was found.

3.4 | Further development of the construction method

During the progression of the project further experimental as well as numerical investigations were required. Two series of pull-out tests, a further series of large-scale bending tests as well as a series of joint compression tests were performed. Both full shells, the test structure and concrete shell bridge “AM2,” as well as the associated experiments are shown in Figure 8.
4 | STATIC CALCULATIONS

Static calculations with different finite-element calculation programs were performed for the geometry optimization, the transformation process from a flat plate to a double curved shell and for the building condition as well as for the final construction state.

4.1 | Simulation of the transformation process

The bending process of the hardened concrete plates was mainly evaluated with preliminary performed four-point bending tests on 100 to 120 mm thick concrete plates with a dimension of 4.5 m by 0.6 m. The test setup is shown in Figure 9. Stainless steel ropes with $7 \times 19$ wires and glass fiber reinforced polymer (GFRP) bars were determined as the most suitable reinforcement types. The detailed evaluation of the bending tests is explained in.\textsuperscript{16} GFRP bars with 8 mm diameter were chosen as reinforcement in radial direction for the initially flat plate of the shell bridge. GFRP bars have the practical advantage that they can be installed in a conventional manner on construction site. In contrast, stainless steel ropes have a low stiffness and have to be prestressed limiting their application to a straight geometry between the anchor points. In addition to the bending experiments, finite element calculations with consideration of the nonlinear material behavior were performed. They were used to predict the transformation behavior from a flat plate to a double curved shell. The calculation model and the material properties were calibrated according to the four-point bending experiments. The main challenge was to achieve the large deformations, which occur during the transformation process. The flat plate of the shell bridge built in Carinthia with the plane dimensions of 56.0 m by 43.0 m by 0.1 m was transformed to a shell with the dimensions of 53.0 m by 38.1 m and a center height of 7.6 m. Due to the double

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure7}
\caption{Top view and cross section of the final design\textsuperscript{23}}
\end{figure}
symmetric geometry of the plate only a quarter was modelled (Figure 10 [left]). The finite-element mesh of the flat plate for the calculation of the construction of the shell bridge “AM2” is shown in Figure 10 (right). The air pressure was modelled as a distributed load. Quadratic hexahedron elements were used for the discretization. The element height was chosen with the thickness of the flat concrete plate (100 mm) and the elements were formulated as shells. Stresses over the thickness were neglected. Each element had nine integration points in plane and eight over the thickness of the elements. In total, one element had 72 integration points. The shell elements have the advantage of significantly lower integration points in comparison to volume elements leading to a lower calculation time. One-dimensional elements were used to simulate the reinforcement bars and the posttensioning cables. The nonlinear analysis was performed by using a Newton Raphson calculation approach. The tangential stiffness matrix was calculated in each iteration step. The deformations in step 50 and step 166 are shown in Figure 11. The maximal calculated compressive strains in the concrete was determined to 1.06 ‰ and the maximum compression strain in the preliminary four-point bending experiments to >3.0 ‰, thus, resulting in a safety factor of 3. The occurring strains were monitored in three different reinforcement bars. The maximal strain in the calculation was determined to 5 ‰. The fracture strain of the bars depends on the manufacturer but is usually >15.0 ‰, resulting again in a safety factor of 3 (GFRP bars have a linear elastic material behavior right up to the moment of fracture). In comparison to the real transformation process on the building site in Carinthia, the simulated form showed a higher curvature in the upper area close to the middle plate and lower curvature in the areas close to the outer rim. On the construction site, an additional conventional reinforcement was assembled in the area of the middle plate and at the intersection of the middle plate to the elements leading to a higher stiffness in these areas and to a slightly different geometry of the bridge in comparison to the calculation.

4.2 | Static calculations of the final structure

A linear elastic material model was used for the calculation of the internal forces during the construction as well as the final construction state in order to dimension the shell structure. The stiffness of the shell was adapted area by area according to the stress level for the calculation of the deformations. The deformation behavior is shown in Figure 12 (right). A possible asymmetric vertical and horizontal earth
pressure was considered in the calculation to cover a varying density and compaction of the earth backfilling. Creep, shrinkage and also temperature effects were taken into consideration in all possible combinations. A stability analysis showed a buckling load factor of 22.1 for the first eigenmode for a nonlinear load increase until buckling. A linear elastic material model was used for the buckling analysis and also here creep, shrinkage and temperature effects were taken into consideration. The first eigenmode was applied as imperfection with an amplitude of 400 mm (Figure 12 left) to take inaccuracies within the construction into consideration.

5 | CONSTRUCTION PROCEDURE

The complete construction procedure is shown in Figure 13. In the first step of the preparatory works, the foundations were built (1). In the second step a granular subbase topped by a flat smoothened concrete plate, which serves as a tension plate during the building stages, was manufactured (2). The third step consisted of the placement of the foil serving as pneumatic formwork, the single curved formwork as well as the reinforcement on top (see Figure 14) before casting the flat concrete plate (3). The single curved formwork for the flat plate was produced by using a numerically controlled mill to comply with the specified accuracy. A very accurate production of the flat plate is of utmost importance as the flat plate directly reflects the accuracy of the final shell structure. Spacers made of a mixture of epoxy resin and sand were mounted between the elements after stripping the formwork of the flat plate. Additional temporary steel profiles were fixed to the elements to avoid a transversal displacement of the elements in the course of the lifting process from the flat plate to the designed double curved shell (red profiles in Figure 15). These profiles were rented parts and were returned to the formwork company after completion of the transformation process. The surface of the shell was high-pressure water jetted to ensure a good bonding between the subsequently added concrete layers. In the next step, as shown in Figure 15, the shell was erected with the PFHC construction method by inflating the pneumatic formwork and tensioning the post-tensioning tendons (16 × 150 mm²—ST 1660/Y1860) with four jacks placed at
two anchor blocks found at the circumference of the structure. An air pressure of 29 to 32 mbar in the air cushion, produced by high-performance fans, was sufficient to perform the transformation process. The erection from the flat plate to the double curved shell was completed after only 5 hr. Subsequently the joints were filled with grout and the tendons were posttensioned to a calculated force. Furthermore, the area at the floor connection was roughened and a small abutment was cast to secure the thin shell against horizontal displacements. Then additional reinforcement was placed on top of the shell in the relevant areas. A special reinforcement was drilled into the foundation to absorb the bending forces and the horizontal forces at the intersection of the shell and the foundation. The additional reinforcement (two layers) and the additional concrete (three layers) were applied subsequently (step (5) through step (8)). Step 8 includes the second and third (top layer). Shotcrete was used in the areas with a higher slope and conventional pump concrete in the areas with a lower slope. The border between shotcrete and pump concrete was set with 25°–28°. The air cushion used as the lifting device was inflated again during the concreting work to support the 100 mm thin concrete shell. The final thickness of the shell added up to 450 mm (including the 100 mm of the inflated concrete shell). In the following work steps, the cut-outs were fashioned (9) and the edge beam was cast (10). In the last step the earth back-filling was produced (11). Figure 16 shows the finished structure.

6 | MONITORING CONCEPT

The shape of the shell was steadily supervised by 3D laser scans from the inside for the purpose of assessing the changes during the complete construction process. The measured 3D point cloud was approximated by a B-spline surface in order to be imported into a finite-element structural analysis software, thus, allowing the analysis of the static behavior of the built structure. The results showed only small changes of the internal forces compared to the designed structure with a very minor impact on the static behavior.
7 | CONCLUSIONS

Concrete shells are very efficient structures once built, but the high effort of production of the needed double curved formwork is responsible for the mere rareness of actual existing constructions. The PFHC building method provides an alternative way for building shell structures with positive Gaussian curvature with high accuracy without requiring the labor and material intensive formwork. The construction method was optimized by numerous preliminary small-scale tests as well as two large-scale tests. Thereafter, the method found its first practical application with the Austrian Railways (ÖBB) resulting in a shell bridge with a span of 36.2 m. The present paper summarizes the different development steps including the form finding, static calculations, construction procedure, and the monitoring concept for the successful implementation of the project. A two-step construction was chosen. First an event canopy was built as a test structure and subsequently the shell bridge “AM2” over the newly built two-rail track Koralmbahn was successfully erected in Austria.

ACKNOWLEDGMENTS

The research project “Freiformflächen aus Beton” was funded by the Austrian promotion agency (FFG) and the authors want
to gratefully acknowledge the financial support. The construction project around the shell bridge “AM2” was built on behalf of the Austrian Railways (ÖBB). The authors want to thank all involved persons for the good cooperation. They want to especially thank the initiator of the project DI Dr. Hannes Kari, the project leader DI Gerald Zwittnig, DI Karin Gradenegger, subject specialist DI Gerald Oberlerchner, and the construction management DI (FH) Gerhard Schett und DI Manfred Joerg. The authors also want to thank the partner engineering office during the designing stages Öhlinger + Partner Ziviltechniker Ges.m.b.H, represented by DI Hinko Jusufagic, Andreas Zerzawy, and Herrn Reinhard Buersch. In addition, the authors want to thank DI Dr. Stefan Kuss and DI Dr. Welf Zimmermann from the supervising engineering office ZKP ZT GmbH and DI Herbert Gaube from GDP ZT GmbH. Further the authors want to thank the company Tecton, represented by Ing. Günter Breibert, DI Christian Müller and Julia Sattler. The authors want to especially thank DI Thomas Pachner from patonic, Grieskirchen for the very good cooperation during the geometry optimization of the shells and Martin Ritt, MA from designkollektiv, Vienna for the development of the design concept of the event canopy.

REFERENCES

1. Muttoni A, Lurati F, Ruiz MF. Concrete shells—Towards efficient structures: Construction of an ellipsoidal concrete shell in Switzerland. Struct Conc. 2013;14:43–50. https://doi.org/10.1002/suco.201200058.
2. Mathis, HD-I. 1987. Shuttering for making constructions of pourable materials, e.g. concrete. EP0182212A3.
3. Bini, D. 1969. Method for erecting structures. US3462521A.
4. Haim, H. 1972. Inflatable Forms. US3643910.
5. Hale, L.E. 1988. Method of constructing a reinforced concrete structure. US4746471A.
6. Harrington, H. 1973. Inflatable form for concrete building shell. US3719341A.
7. Head J. No nails, no lumber: The bubble houses of Wallace Neff. Chronicle Books, New York: Princeton Architectural Press, 2012.
8. Nicholls, RL. 1984. Air-inflated fabric-reinforced concrete shells. US4446083A.
9. Schlaich, JPDI, Bergermann, RDI. 1986. Pneumatische schalung. DE3500153A1.
10. South, DB, South, B. 1979. Building structure and method of making same. US4155967A.
11. Kromoser B, Huber P. Pneumatic formwork systems in structural engineering. Adv Mater Sci Eng. 2016;2016:1–13. https://doi.org/10.1155/2016/4724036.
12. Gramazio, F, Kohler, M, Willmann, J, Oesterle, S, Vansteenkiste, A, Mirjan, A. 2012. Zero waste free-form formwork. Proceedings of the Second International Conference on Flexible Formwork. Presented at the Second International Conference on Flexible Formwork, Bath, United Kingdom.
13. Mainka J, Kloft H, Baron S, Hoffmeister H-W, Dröder K. Non-Waste-Wachsschalungen: Neuartige Präzisionsschalungen aus recyclierbaren Industrie- wachsen. Beton- Stahlbetonbau. 2016;111: 784–793. https://doi.org/10.1002/best.201600055.
14. Gericke, O, Kovaleva, D, Sobek, W. 2016. Fabrication of concrete parts using a frozen sand formwork. Proceedings of the IASS Annual Symposium 2016, “Spatial Structures in the 21st Century.” Presented at the IASS Annual Symposium 2016, Tokyo.
15. Schipper R. Double-curved precast concrete elements: Research into technical viability of the flexible mould method (Dissertation). Delft, Netherlands: TU Delft, 2015.
16. Kromoser B, Kollegger J. Aktives Verformen von ausgehärteten Betonelementen zur Herstellung von räumlich gekrümmten Betonflächen. Beton- Stahlbetonbau. 2017a;112:106–115. https://doi.org/10.1002/best.201600049.
17. Kromoser B, Kollegger J. Pneumatic forming of hardened concrete – building shells in the 21st century. Struct Concr. 2015;16: 161–171. https://doi.org/10.1002/suco.201400057.
18. Kromoser B, Kollegger J. Herstellung von Schalentragwerken aus Beton mit der “Pneumatic Wedge Method”. Beton- Stahlbetonbau. 2014;109:557–565. https://doi.org/10.1002/best.201400014.
19. Kromoser, B, Kollegger, J. 2019. Die praktische Umsetzung von neuen ressourceneffizienten Bauverfahren als Katalysator für Innovation im konstruktiven Ingenieurbau. Festschr. Zum 60 Geburtstag Von Konrad Bergmeister. Vienna, Austria: Oliver Zeman. https://doi.org/10.1002/cepa.960
20. Kromoser, B, Pauser, M. 2014. Freiformflächen aus Beton (Final Report No. Projekt Nr 844563).
21. Kromoser, B, Kollegger, J. 2017b. How to inflate a hardened concrete shell with a weight of 80 t. Proceedings of the IASS Annual Symposium 2017, “Interfaces: Architecture. Engineering. Science.” Presented at the IASS Annual Sym, Hamburg, Germany.
22. Kromoser B, Pachner T, Tang C, Kollegger J, Pottmann H. Form-finding of shell bridges using the Pneumatic Forming of Hardened Concrete construction principle. Adv Civil Eng. 2018b;2018:1–14. https://doi.org/10.1155/2018/6309460.
23. Kromoser B, Kollegger J. Entwurf, Geometriepsimierung und Bemessung der Wildbrücke AM2 hergestellt mit PFHC. Beton- Stahlbetonbau. 2018;113:88–95. https://doi.org/10.1002/best.201700068.
24. Evolute GmbH. 2019a. Evolute | the geometry experts [WWW Document]. Available from: http://www.evolute.at/ (accessed 10 November 2018).
25. Evolute GmbH. 2019b. Evolute | the geometry experts [WWW Document]. Evol. Geom. Experts. Available from: http://www.evolute.at/ (accessed 5 May 2019).
26. Robert McNeel & Associates. 2019. Rhino 6 for Windows [WWW Document]. Available from: https://www.rhino3d.com/en/ (accessed 5 May 2019).
27. Kromoser B, Kollegger J, Kari H, Gradenege K, Ganster M. Ein innovatives Betonschalensbauverfahren in Anwendung: Herstellung der Wildbrücke AM2 mit PFHC. Beton- Stahlbetonbau. 2018a; 113:222–232. https://doi.org/10.1002/best.201700069.

AUTHOR BIOGRAPHIES

Benjamin Kromoser
Institute of Structural Engineering
University of Natural Resources and Life Sciences, Vienna
Peter-Jordan-Straße 82
1190 Vienna, Austria
benjamin.kromoser@boku.ac.at

Johann Kollegger
Institute for Structural Engineering
TU Vienna
Karlsplatz 13, E212-2
1040, Vienna, Austria
johann.kollegger@tuwien.ac.at

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Kromoser B, Kollegger J. Efficient construction of concrete shells by Pneumatic Forming of Hardened Concrete: Construction of a concrete shell bridge in Austria by inflation. Structural Concrete. 2020;21:4–14. https://doi.org/10.1002/suco.201900169