The use of LS-DYNA for the development of a topology-optimized thin-walled shell structure manufactured by Die-Less-Hydroforming

Andreas Metzger[1], Thomas Ummenhofer[1]

[1] Karlsruhe Institute of Technology, KIT Steel & Lightweight Structures,
Research Center for Steel, Timber & Masonry, Otto-Ammann-Platz 1, 76131 Karlsruhe, Germany

1 Introduction and idea

Within the framework of sovereign research at the KIT Steel & Lightweight Structure and an accompanying research project [1], the aim was, following an idea by Ummenhofer and Metzger, to develop a hinged column with a cross-section tapering from the centre to the two ends. The result is an elegant minimalistic pillar called "Hybridstütze PERFECTO" (in English: Hybridcolumn PERFECTO) that is made of an outer thin stainless steel shell, a core of ultra high-strength steel located in the cross section center and a filling of the space in-between by self-compacting concrete.
The Hybridcolumn PERFECTO was first released at the BAU Munich in January 2019 and some photos are given in Fig.1: For further details see [2].

(b)

(a) (c) (6)

Fig.1: Hybridcolumn PERFECTO consisting of a stainless steel outer shell manufactured by the innovative process Die-Less Hydroforming: (a) Presentation at the joint trade fair stand of "Informationsstelle Edelstahl Rostfrei" at BAU Munich 2019. (b) Surface detail. (c) Filigree base joint detail. (d) Exhibition in the historical building of the Civil Engineering Faculty at KIT. (Source: [3])

The hybrid load-bearing concept of PERFECTO consists of a bar with circular cross section made of ultra high-strength steel, which is supported by the stiff concrete surrounding it and preventing buckling of the bar. Consequently, the bar can be stressed to its plastic limit load similar to an equivalent tension bar. The name of the newly developed hinged pillar, PERFECTO, is based on a classic cigar shape that resembles the basic shape of the column. In detail, this special shape of the

column is directly adapted to the resulting moment from bow imperfections and the corresponding buckling figure in Eulerfall II ("hinged support") for the axial load case and enables filigree connection points due to its minimal cross-sectional dimensions at both ends.
The manufacturing of such a shaped thin shell with big dimensions suitable for building construction applications and in smaller quantities usually required there, is not economically possible with conventional forming processes such as deep drawing of two half-shells and subsequent welding.
On the one hand, huge presses would be required for these relatively large blank dimensions, which would also have to provide the necessary press closing forces. On the other hand, these conventional forming processes are often only economically viable for a very large number of identical pieces due to the planning and production costs of the required forming tool, and this effect is even more pronounced with very large blank dimensions. However, in the building sector usually only small quantities of identical components are required adapted for each individual building project.
For these reasons, the manufacturing of the outer thin shell of the Hybridcolumn PERFECTO is carried out by an innovative forming process known as Die-Less Hydroforming.
Within **Die-Less Hydroforming**, two or more flat thin identical sheet metal blanks are laid one on top of the other in a congruent way and joined at their common edges by welding with a seal-weld. The resulting still flat double-layered blank is then transformed into a spatial object by continuous internal pressure increase. No forming tools and consequently no presses are used, which means that even large objects can be produced economically. Due to the fact that for the initial flat double-layered blank almost any geometry can be applied, which in turn can be used to produce complex structures that can hardly be produced with other conventional processes, and since the required equipment is very simple, Die-Less-Hydroforming enjoys great popularity among numerous users from various fields of application.
Therefore, the thin-walled stainless steel shell of PERFECTO is also produced from two thin flat steel blanks, which are laid congruently one on top of each other and welded together at the common edge. Subsequently, a spatial structure is created by pressing water into the gap between the metal sheets. This process takes place without the use of forming tools.
Within this paper the usage of the explicit LS-DYNA forming-simulation for developing the thin-walled outer shell structure for the innovative hinged pillar PERFECTO is presented. Through extensive forming simulation studies, the geometry of the initial double-layered blank could be optimized in such a way that the spatial shape resulting from the Die-Less Hydroforming process does not cause any wrinkles and buckles, as it is often the case with other objects produced by Die-Less Hydroforming. The presented results come both from sovereign research on Die-Less-Hydroforming at KIT Steel & Lightweight Structures by Ummenhofer and Metzger [3] as well as from [1].

2 Summary of the FEM-Forming-Model and the modeling approach

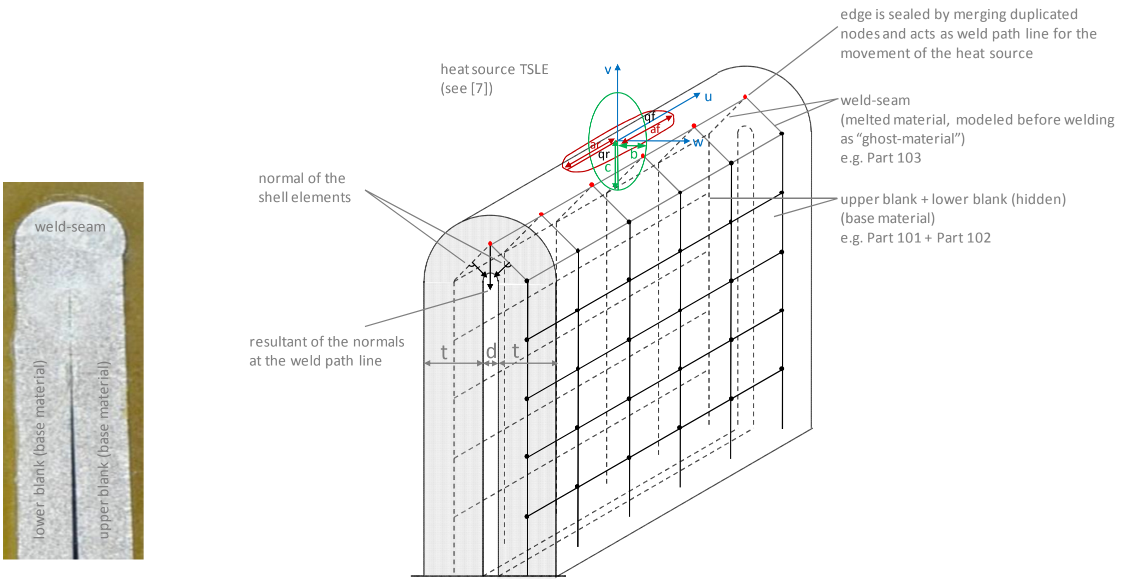


Fig.2: Modeling scheme of a double-layered Die-Less-Hydroforming blank ([5],[4], originally from [6], edited) including heat source for welding & corresponding exemplified macro-section of the edge weld, additional fixation equipment is not illustrated

Recently, the authors have presented an entire process chain simulation for Die-Less-Hydroforming including welding (LS-DYNA implicit and DynaWeld® for preprocessing) and forming (LS-DYNA explicit). In this paper the focus is on the forming simulation with LS-DYNA explicit.
The modeling approach developed for this purpose, which can also be used for a thermo-structural-mechanical welding simulation, is shown in Fig.2:.
The special feature of the explicit forming simulation is that the internal forming pressure is applied by the LS-DYNA keyword **`*AIRBAG_LINEAR_FLUID`** available from the airbag simulations via a mass input vs. time curve additionally using the mass and time scaling approaches usual in forming simulations. For further information please refer to [4], [5] and [6], among others.

3 Selected specimen and parameter definition

Within the scope of research at KIT, investigations with different blank geometries are carried out, two selected specimens termed WA1 or 0160 made of stainless steel are presented below. The specimen WA1 has to be regarded as a research object for the investigation of the special buckling phenomena occurring during the Die-Less-Hydroforming process, whereas the specimen 0160 is optimized by extensive LS-DYNA simulations and can be used directly for the Hybridcolumn PERFECTO.
The specimen WA1 was produced in the course of sovereign research at the KIT through step-by-step manual TIG hand-welding without filler material. The specimen 0160 was produced within the scope of [1] by Seyfried Metallbau GmbH, Calw.
For both specimens, the blank length is approximately identical. For WA1 the blank width in the middle of the specimen is defined as B_{WA1} and the sheet thickness as t_{WA1}, whereas for 0160 they are defined as B_{0160} and t_{0160}. The interrelations are: $B_{WA1} >> B_{0160}$ and $t_{WA1} > t_{0160}$. For the preparation of the double-layered Die-Less-Hydroforming blank for the forming simulation, the CNC-cutting-line is slightly shifted inwards to take into account the material burn-up during welding as well as the position of the shell middle surface according to the modeling approach (see Fig.2:).
The definition of the parameters d_{mid}, d_{weld} and d_{ideal} according [3], which can be used for the description of the Die-Less-Hydroforming process and its individual states, is illustrated in Fig.3: The normal distance between the two blanks (in z-direction) along the longitudinal axis (x-direction) is defined as d_{mid} and the distance between the two weld-seam edges (in y-direction) is defined as d_{weld}. These values can be evaluated for any position/cross section in the longitudinal direction of the double-layered blank and are evaluated in the following for the blank center (x=0).
For that forming state, in which the cross-section in the middle of the specimen is approximately circular and assuming that no plastic membrane strain occurs in the circumferential direction of the specimen, an ideal diameter d_{ideal} can be calculated as an analytical approximation by setting two times blank width B equal to circumference U.
At the beginning of the forming process, i.e. when the two blanks lie directly one upon each other, d_{mid} starts at approximately 0. When considering the initial distance of the shell middle surfaces in the FE model, d_{mid} corresponds exactly to the sheet thickness t. The value d_{weld} starts at the blanks width B.

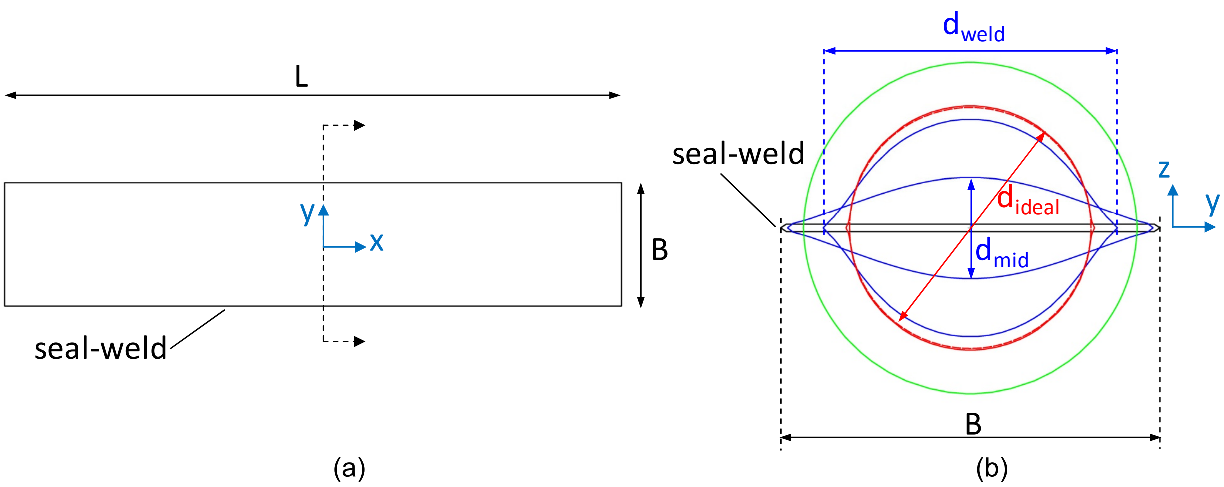


Fig.3: General parameter definition for describing different forming states of the double-layered Die-Less-Hydroforming blank during the inflation process: (a) Top view. (b) Cross section view. (Source: [5], originally from [3], edited)

4 Experimental investigations

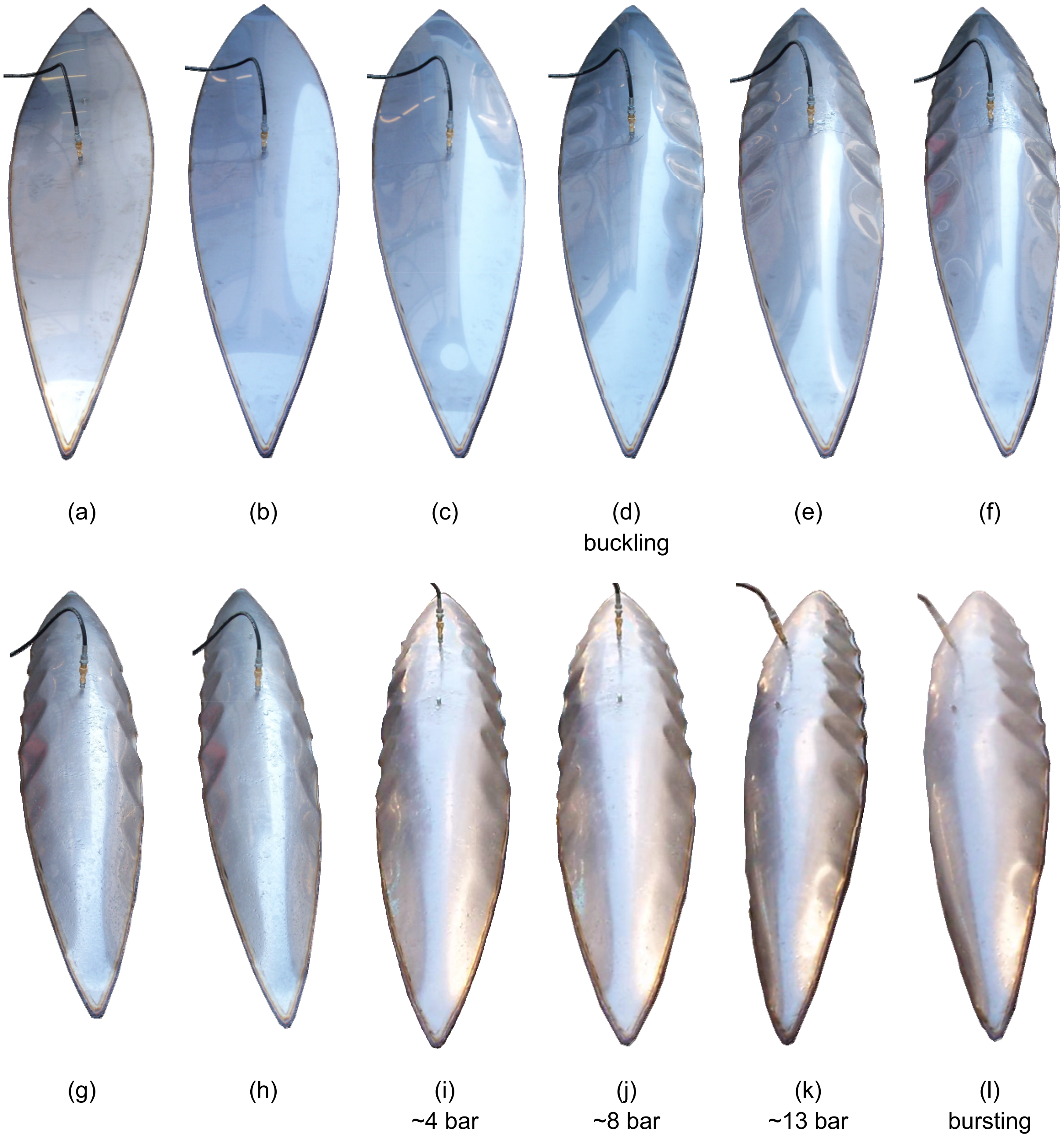


Fig.4: Sequence of the forming experiment with specimen WA1 showing the characteristic buckling phenomena of rod-shaped Die-Less-Hydroforming objects. Note: Images (i) to (l) show the specimen from the opposite direction. (Source: [3], edited)

For **specimen WA1**, the sequence of the forming experiment is shown step by step in Fig.4:. During the forming process, an internal pressure-time behavior, that is typical for Die-Less-Hydroforming of rod-shaped test specimens, is manifested: At the beginning, the pressure remains almost constant for a long time in a very low range (< 2 bar), the spatial deformation of the double-layered Die-Less-Hydroforming blank takes place. Only when the cross-sections have largely reached an almost circular shape over the entire length, the internal pressure rises strongly, i.e. plastic membrane strain occurs in the circumferential direction.

A double-conical pressure vessel is now present, so to speak, in which, similar to a burst test with constant mass input, the internal pressure increases almost vertically asymptotically and failure occurs in the form of a longitudinal rupture due to the stress relationships known from the “boiler formula”

(Barlow's formula). For Die-Less-Hydroforming objects, failure due to local tearing in the weld seam occurs directly in most cases. Rarely, but also possible with excellent weld seam quality, failure due to bursting in the base material can happen.
The dimensions of the specimen WA1 are selected so that during inflation a buckling pattern, which is very characteristic for rod-shaped Die-Less-Hydroforming objects, occurs at the edges of the double-layered blank. The resulting buckling pattern represents a functional and aesthetic impairment of the shell and seems to make the resulting structure unsuitable for the desired application as a pillar in building construction. The assessment of the aesthetic impairment caused by the buckling pattern is, of course, solely up to the taste of the individual observer, i.e. how strongly he perceives this as a disturbance. In this context it should be pointed out that many Die-Less-Hydroforming objects exist especially in the field of art and (functional) design, which are advertised as unique by their creators on the basis of this special buckling optic. However, there is no doubt, that the hollow body object resulting from the chosen blank dimensions of WA1 does not fulfill the desired requirements of a building column with regard to its proportions and dimensions (slenderness, aesthetics and filigree character), as they are requested for the outer shell of the Hybridcolumn PERFECTO.

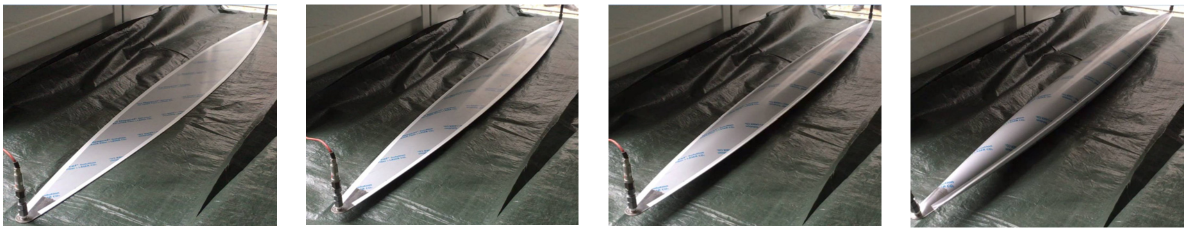


Fig.5: Sequence of the forming experiment with specimen 0160 resulting in a completely buckle-free Die-Less-Hydroforming object that can be used as an outer shell for the Hybridcolumn PERFECTO (Source: [2])

The CNC contour line for cutting the blanks of **specimen 0160** and the corresponding suitable sheet thickness were determined in advance by extensive parameter studies with LS-DYNA within the scope of [1] and [3], respectively. The objective was to use the resulting Die-Less-Hydroforming structure as the outer shell for the Hybridcolumn PERFECTO, with the requirement that on the one hand no buckling occurs during forming and that the spatial object has adequate dimensions for a pillar in terms of slenderness, aesthetics and filigree character. Fig.5: shows the forming procedure step by step and it can be seen that no buckling occurs. The principle sequence of the forming process of specimen 0160 with regard to internal pressure development and forming behavior corresponds to the general principles for rod-shaped Die-Less-Hydroforming objects described above. During the forming test, a continuous internal pressure measurement was carried out. For specimen 0160, several series of forming tests with identical blank geometry were carried out, and the internal pressure-time curves correspond excellently both qualitatively and quantitatively to each other and also match the values from the simulation with regard to course and order of magnitude.

5 Some simulation results in extracts

Within the scope of an extensive FEM parameter study, the formation of the buckling pattern as a function of the B/t ratio for a double-layered Die-Less-Hydroforming blank is investigated in [3]. In the following, representative results of the forming simulation for the two specimens WA1 and 0160 are presented.
Fig.6: shows the development of the parameters d_{mid} and d_{weld} for the test **specimen 0160** for different mesh refinements of the double-layered Die-Less-Hydroforming blank, evaluated as a function of the internal forming pressure. The two characteristic values d_{mid} and d_{weld} approach the ideal diameter d_{ideal} from below and above, respectively, in order to reaching afterwards together the technical range that can be used for the outer shell of the Hybridcolumn PERFECTO. This is followed by a joint re-increasing of d_{mid} and d_{weld} combined with an intensive reduction in sheet thickness up to local necking which finally ends in the abrupt bursting of the structure.
Some essential forming states of specimen 0160 are shown in Fig.5:, on the one hand for the configuration also carried out in the experiment (cf. Fig.5:) with sheet thickness $t_{0160,}$ and on the other hand, for a configuration with a reduced sheet thickness $t_{0160,reduced} \approx 0.8 \cdot t_{0160}$. No buckling occurs in the configuration with t_{0160} as in the real experiment. However, with identical blank geometry 0160 but with a reduction of the sheet thickness to $t_{0160,reduced}$, the formation of the characteristic buckling pattern

can be investigated in the simulation. This buckling pattern completely disappears with the increasing internal pressure in the later simulation states, whether this is the case in reality remains to be doubted. In any case, it can be assumed that in the real forming process, the appearance of a buckling pattern will probably have a negative influence on the subsequent forming process concerning flatness quality and external appearance of the thin-walled structure.

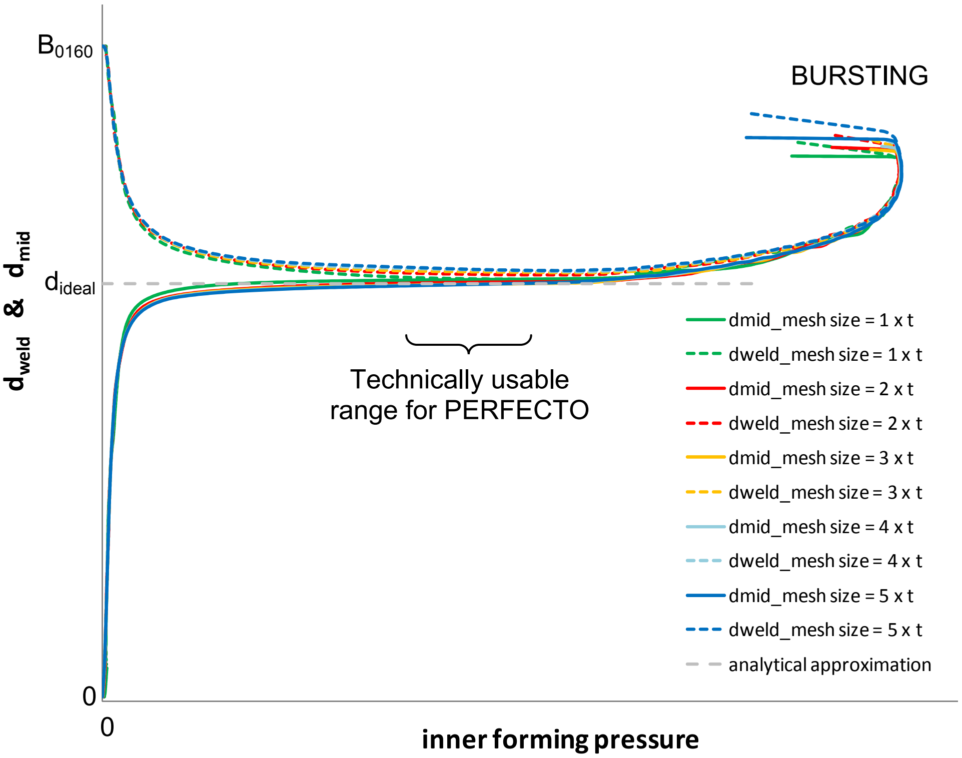
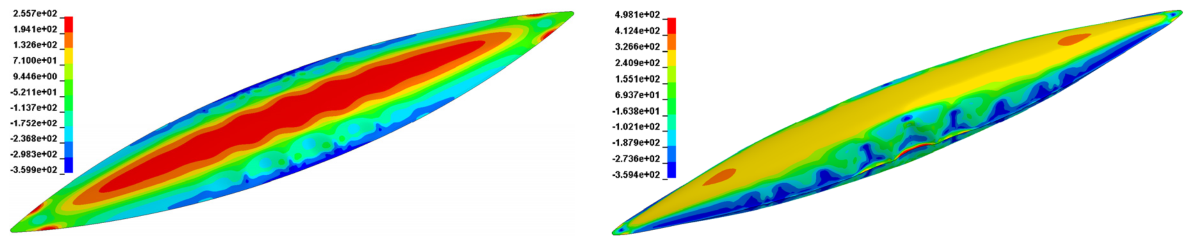


Fig.6: Relative development of d_{mid} and d_{weld} vs. inner forming pressure load for specimen 0160 with sheet thickness t_{0160} and different mesh refinement configurations (Source: [3], edited)

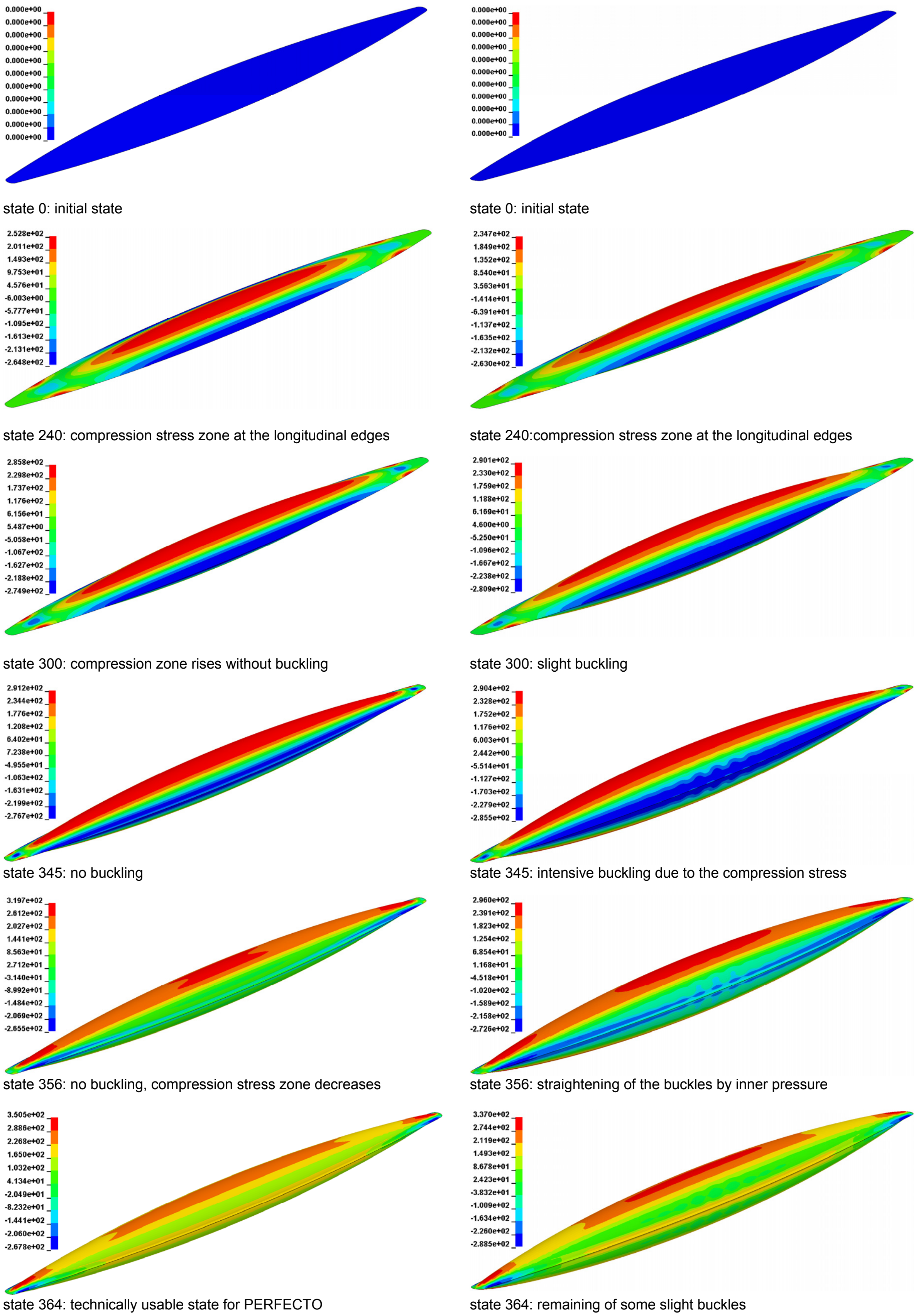
The formation of a characteristic buckling pattern can also be observed for **specimen WA1** (with sheet thickness t_{WA1}) both in simulation (c.f. Fig.7:) and in the experiment (see Fig.4:) at a relatively early forming stage. Afterwards, a very long forming phase with an intensification of the buckling pattern takes place. The straightening of the buckles by the increasing inner forming pressure, which is also present here in the simulation, cannot be achieved in the experiment due to insufficient weld seam quality. In the experiment, failure occurs early in the phase of the almost vertical asymptotic increase of the inner forming pressure due to fracturing in the weld seam. In order to achieve the straightening of the buckles in reality, a weld seam with special strength and deformation properties would be required. Due to the dominant and temporally as well as spatially strongly manifested buckling pattern of WA1, which probably causes a local multi-axial stress state in the weld seam, the execution of such a weld seam is technically demanding and may not be successfully feasible.
As an alternative option, the parameter study carried out in [3] shows that for the blank geometry of WA1, the sheet thickness would have to be increased from t_{WA1} to 1.8 • t_{WA1} so that no buckling occurs during the forming process.



(a) early buckling state (0,948 Bar, state 195)

(b) later buckling state (12,2 Bar, state 340)

Fig.7: Simulation results of specimen WA1 showing characteristic buckling plotted in true stresses [MPa] in global longitudinal direction (mid-plane integration point) (Source:[3])



(a) specimen 0160 with sheet thickness t_{0160}

(b) specimen 0160 with sheet thickness $t_{0160,reduced}$

Fig.8: True stresses [MPa] in global longitudinal direction of specimen 0160 (mid-plane integration point) for different states during the inflation with identical mass vs. time input rate (Source:[3])

6 Summary

During the manufacturing of the thin-walled outer shell for the Hybridcolumn PERFECTO by Die-Less-Hydroforming of double-layered blanks of stainless steel, a characteristic buckling pattern can occur. Through the development of a modeling approach and a simulation model for Die-Less-Hydroforming and accompanying parameter studies with LS-DYNA, the formation of this characteristic buckling pattern can be detected and the resulting spatial support geometry can be previously determined by simulation. Thus, enormous costs for experimental tests can be saved and the production of buckling-free outer shells for the Hybridcolumn PERFECTO can be realized by Die-Less-Hydroforming for different individual project-related designs with regard to length and diameter.

7 Literature

[1] KIT Steel & Lightweight Structures, Research Center for Steel, Timber & Masonry & Seyfried Metallbau GmbH Calw: "Hybride filigrane stabförmige Bauelemente aus nichtrostendem Stahl und Beton mit hohen ästhetischen Ansprüchen hergestellt durch wirkmedienbasierte Umformung ohne Formwerkzeug", ZIM-Cooperation project supported by *Federal Ministry for Economic Affairs and Energy* on the Basis of a decision by the *German Bundestag,* 02/2015 - 04/2017

[2] KIT Steel & Lightweight Structures, Research Center for Steel, Timber & Masonry: "*Flyer Hybridstütze PERFECTO*", https://stahl.vaka.kit.edu/641.php, 2019, retrieved on April 1, 2019 from https://stahl.vaka.kit.edu/downloads/Hybridstuetze_PERFECTO_FALTBLATT_web.pdf

[3] Metzger, A.: "PhD Thesis (in progress) concerning the topic of Die-Less-Hydroforming", Karlsruhe Institute of Technology, KIT Steel & Lightweight Structures, Research Center for Steel, Timber & Masonry

[4] Metzger A., Ummenhofer, T.: "Process chain simulation for “Die-Less-Hydroforming” including welding and forming with “DynaWeld” and “LS-DYNA”", 11th European LS-DYNA Conference, Salzburg, 2017

[5] Metzger, A., Ummenhofer, T.: "Explicit and implicit Simulations for Die-Less-Hydroforming-Structures including Welding, Forming and Load Capacity using LS-DYNA® and DynaWeld®", 15th International LS-DYNA® Users Conference 2018, Dearborn, 2018

[6] Metzger, A., Ummenhofer, T.: "Schweißsimulation von „Die-Less-Hydroforming“-Platinen mit DynaWeld und LS-DYNA", in: Hildebrand, J., Loose, T. (Publisher), Tagungsband Simulationsforum 2016 Schweißen und Wärmebehandlung, Weimar, 2016, p. 148–156

[7] Loose, T.: "DynaWeld Wärmequellen, PDF-Dokumentation DynaWeld", Ingenieurbüro für Schweißsimulation und Wärmebehandlungssimulation, Dr.-Ing. Tobias Loose, 2016

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