Design to Installation of a free-form roof cladding with a flexible mould.
The building of the public transport terminal Arnhem

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Abstract

In this paper we present a case-study of the recent and ongoing fabrication of doubly-curved GFRC panels for the Arnhem Station which are being produced using a flexible mould system and an innovative digital chain of information developed by the authoring companies.

Keywords:

Data exchange, Digital Information Chain, Cladding design

Synopsis

Using a digital chain to minimize the risk of fail from design to installation, dealing with ±1400 unique panels.
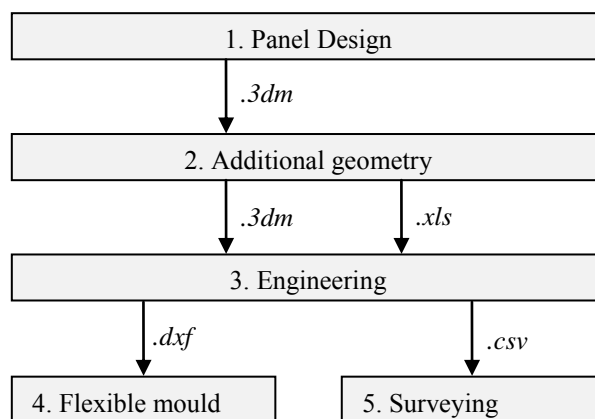

Figure 1 – file formats that carried information in the digital information chain described in the following pages

1. Panel Design (UNStudio)

The unique geometry of the roof structure of the public transfer terminal in Arnhem is emphasized by a panel system that was designed to seemingly weave around the roof and to underline its main geometric features. (see also Van Veen *et al*. [2]).

Starting from a regular grid of parallel lines on the east side representing the underlying office grid of the connecting K4 office building the lines start weaving and curving towards the west side articulating the busy transfer function underneath.

Fields are created between these main curves in which the individual rows weave into each other. Each row then consists of panels of an approximate size of 3.6m x 1.2m each. The long seams are accentuated with a gap of 6cm whereas the seam between two panels of one row are as small as 2cm.

The total system includes around 1400 individual panels which were all generated using custom VBScripts in Rhinoceros 3d.

A numbering system based upon this design with 3x2 digits identifies each individual panel. The ID "11-03-10" refers to field 11 - row 03 - panel 10.
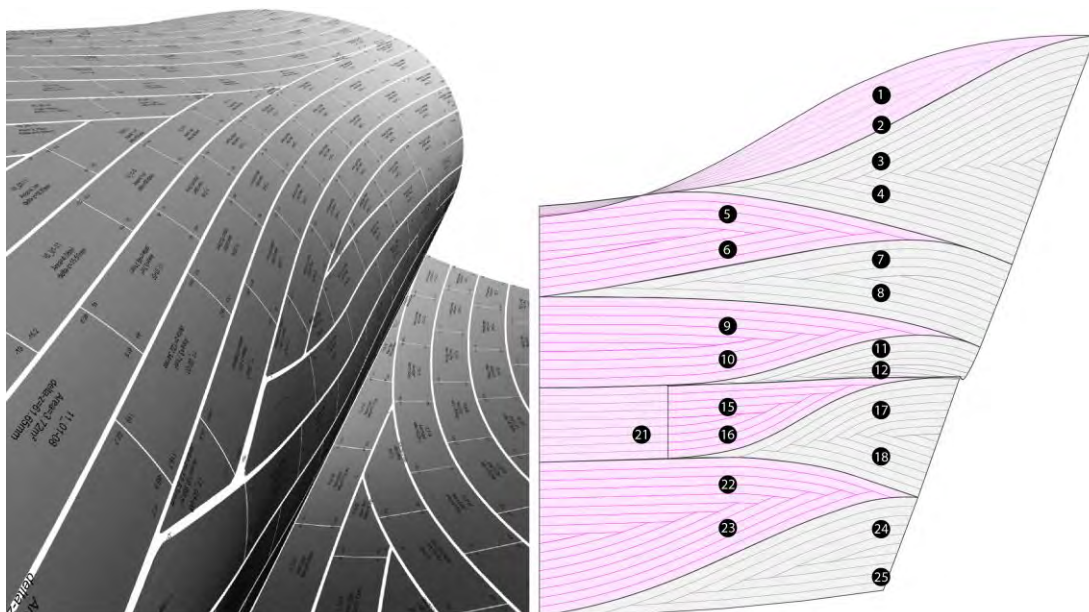

Figure 2 – panel system that was designed

2. Additional geometry (UNStudio)

As all panels were generated using custom scripts it was possible for the architect to generate additional geometry and data along with the panel geometry to make the translation from design surface to engineering of substructure and mould more fluent. A few basic agreements were made between all involved parties about what information was necessary to base the further engineering on this data. For that purpose a terminology was defined to talk about the information in one common language. The following abbreviations and sketches were made to start the process of generating additional geometry.

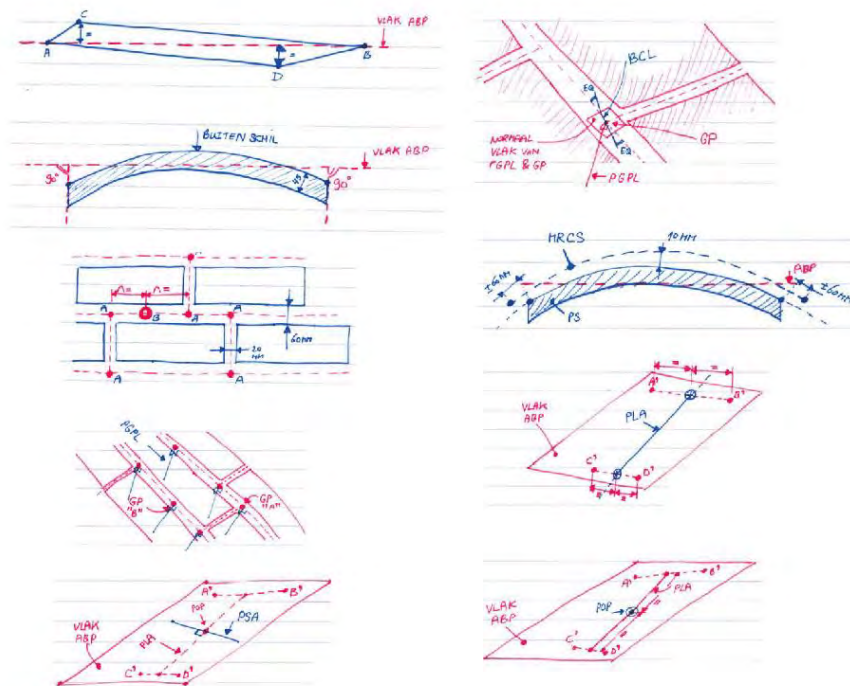|			
ABP	Average Base Plane	MOP	Mould Offset Plane
PS	Panel Solid	MPC	Mould Projected Contour
GP	Gap Point	MRCS	Mould Rib Cut Surface
PGPL	Perpendicular Gap Point Line	PLA	Panel Longitudinal Axis
PSA	Panel Secondary Axis	POP	Panel Origin Point
BCL	Bracket Center Line	P1 – P21	Height adjustable point of framework

Figure 3 – most agreements on the data exchange could be done in simple sketches explaining what the information needed to contain.

To obtain additional geometries from the designed panels each of the required information was translated into VBScripts in Rhinoceros 3d software which extracted the specific data. This way the panel geometry itself was only used for visual purposes and model checks further in the process. The data which defined the panel geometry and the interface with the substructure was much more abstract. For each panel reference lines and planes, points defining bracket attachment, vectors defining normals to the structural shell for surveying, and outlines of the panels were generated. Figure 4 and 5 give a visual impression of that data.
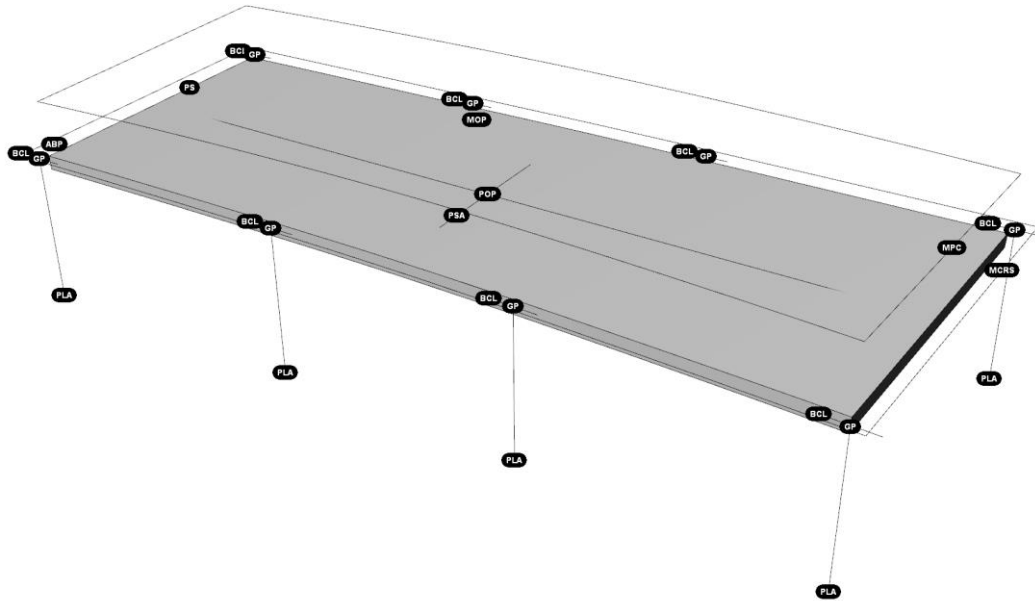

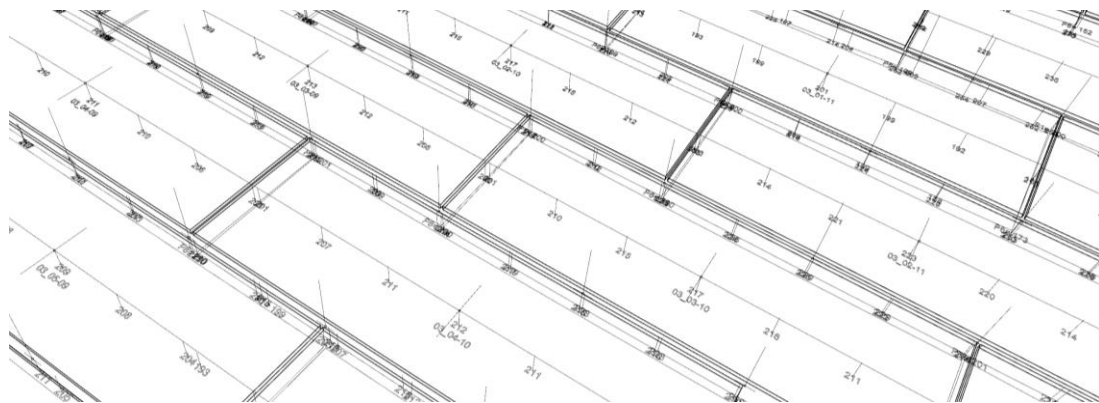Figure 4 – geometric representation of the generated data

Figure 5 – batch of unique panels showing additional geometry

Additionally, information for the flexible mould of every panel was generated. (Figure 6). This information contained 21 Δ-values for the adjustable pins of the mould.
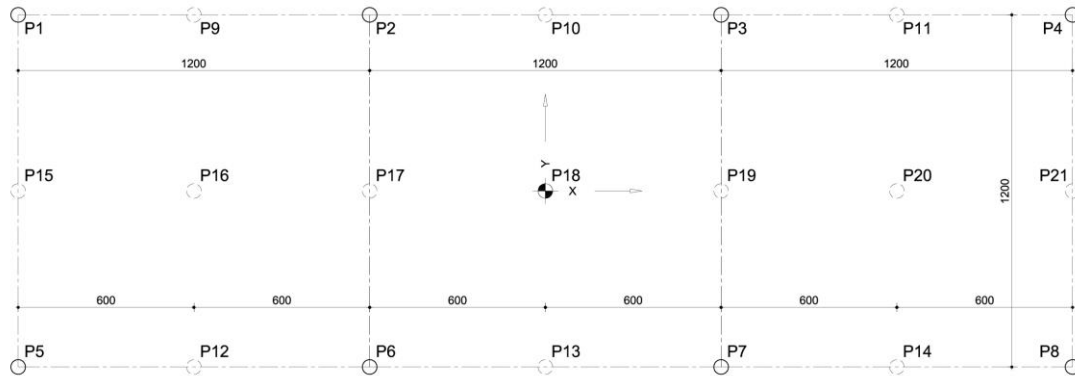

Figure 6: position of the 21 Δ-Z coordinates

All information was then exported as a separate 3DM file for each panel and summed up in an Excel-Sheet (Figure 7) for further processing during engineering.

Batch	Name	revision	angle	Area	measure1	measure2	type	P1	P2	P3	P4	P5	P6	P7	P8
1	04_01-04	-	14.8400599	4.111	1154.39681	3608.21428	DC	200.28977	204.6454	206.057877	206.923982	206.723287	209.36141	206.895092	200.419132
1	04_01-05	-	16.1478396	4.09	1147.04076	3597.42248	R	180.329307	188.043567	195.14366	201.185911	201.164571	197.908118	190.466143	180.346249
1	04_01-06	-	17.9897472	4.091	1146.3425	3597.85035	R	181.281551	190.313906	197.057914	201.262188	201.262888	194.938832	188.022829	181.418241
1	04_01-07	-	19.2183213	4.092	1147.45496	3599.74407	R	192.439666	194.232944	196.185319	201.521449	201.088368	196.421337	193.604757	193.134571
1	04_01-08	-	20.0285584	4.093	1149.10984	3604.54958	R	186.947277	187.299696	192.618648	202.312016	201.897056	195.022816	190.395941	187.851893
1	04_01-09	-	21.3709868	4.092	1148.71014	3606.48023	R	183.299851	187.318558	193.927558	203.544986	202.792824	196.243633	190.49032	184.779166
1	04_02-05	-	16.7846502	4.122	1149.05884	3627.05929	R	200.017699	202.707264	207.422635	215.562671	215.615121	210.756518	205.253108	200.135547
1	04_02-06	-	18.4832246	4.111	1146.87905	3615.13033	R	177.617211	185.793013	193.861524	201.013668	201.115941	194.562153	186.787719	177.625052
1	04_02-07	-	20.6989237	4.113	1147.11169	3617.23726	R	177.062888	187.230663	194.819967	201.168501	201.137362	195.648824	187.478513	177.228018
1	04_02-08	-	23.0204283	4.118	1147.71119	3622.8991	R	199.904475	203.475855	212.390356	229.272442	229.251494	215.52082	205.039461	200.376629
1	04_02-09	-	25.8769357	4.126	1149.46042	3632.6987	R	162.391294	167.605509	180.368944	202.052878	202.077051	185.090969	172.20363	163.049505
1	04_03-05	-	18.3865154	4.138	1147.56315	3639.63825	R	199.756527	202.272659	209.723969	219.989462	220.091297	210.646575	204.459548	199.857239

Figure 7: extraction of the generated Excel file

3. Engineering (Sorba Projects B.V.)

The architects 3DM file, containing the panel design (shell) and additional generated geometry, is imported in Autodesk Inventor®. Properties of each panel in the Rhino-model are also provided as a separate XLS file.

Relative to the provided Gap Points (GP), a smart pattern for the position of the brackets is used as a base for every panel variant. (Figure 8Figure)
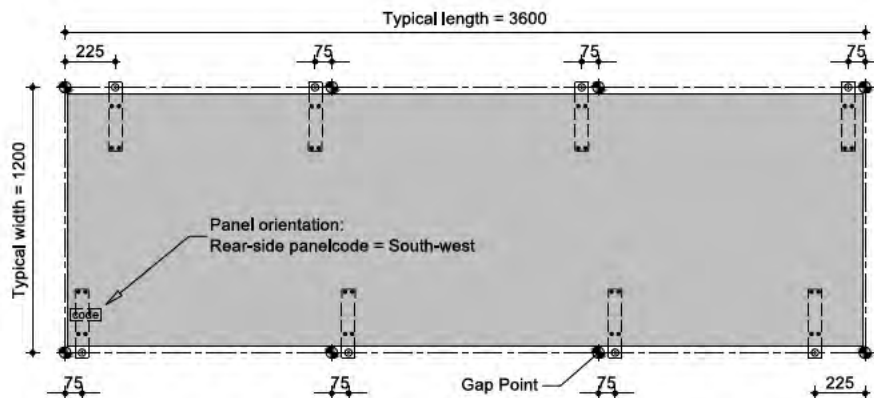

Figure 8: Conflict-free pattern of cast-in steel brackets for each GFRC panel

3.1 Building detailed 3D model

Using the provided geometry it is relative easy to position all substructure parts in the assembly; hardwood blocks, cast-in steel brackets and hanger bolts. (Figure 9)
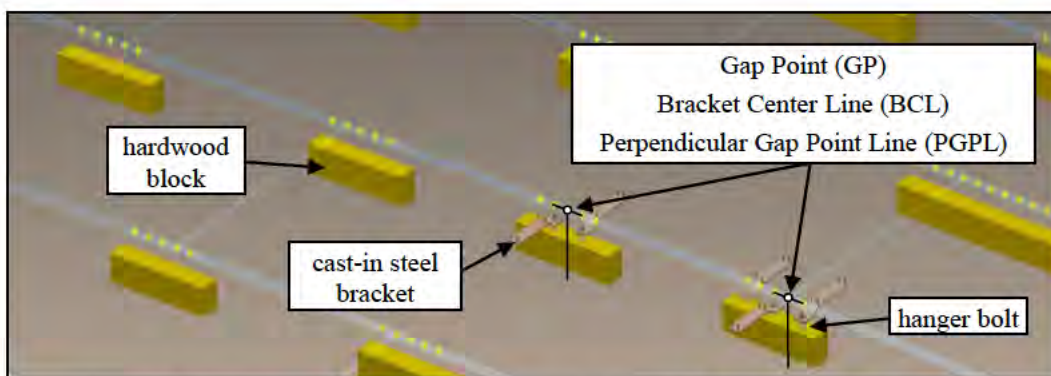

Figure 9: Generated geometry in Rhino for positioning substructure parts in Inventor

3.2 Work preparation flexible mould system

Outlines and heights are combined in AutoCAD and exported to DXF R12 format.

3.2.1 Outlines

For every panel the architect generated additional geometry; the Mould Offset Plane (MOP) contains the projected outline of the panel (MPC), together with the panel axes (PLA & PSA).

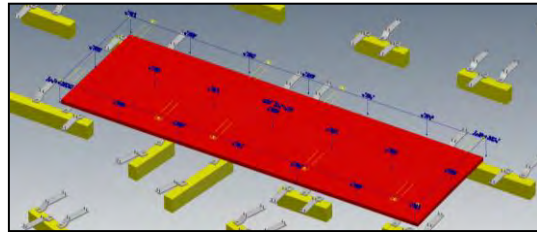In Inventor the projected outline of all brackets are added to the MOP and the sketch is exported to AutoCAD.

Figure 10: Projection of bracket position

3.2.2 Heights

The flexible mould system has a 600x600 mm grid for setting out the panel heights, total of 21 vertical pins.

The architect has generated the height from the MOP to the panel surface for every vertical pin, for every panel. (values stored in separate XLS file)

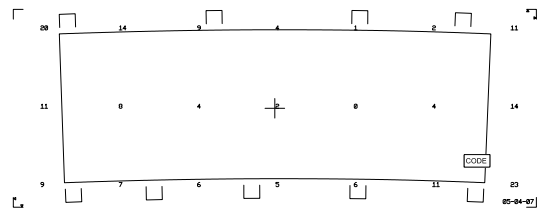In AutoCAD an attributed block with the 600x600 grid is filled with these 21 heights.

Figure 11: DXF file for each panel

3.3 Work preparation building surveying

All hardwood blocks in the 3D model assembly are labelled with an unique code (Figure 12), but are also an instance of the same part. Additional to the hardwood block definition, the part also contains 4 work-points which are needed by the surveyor (Figure).

Using a custom written VBA routine for Inventor, all work-points inside all parts will be exported to a CSV file, translating the coordinates relative to assembly origin and orientation.
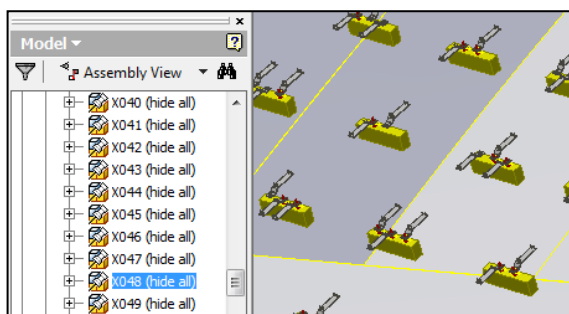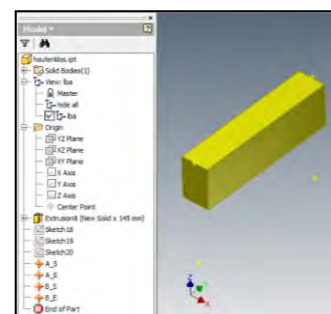

Figure 12: Unique part label in Assembly

Figure 13: Part with points

4. Flexible mould (mbX)

All glass reinforced concrete panels of this project have a different shape, therefore a flexible mould system is designed to make sure 98% of the panels can be made in a smart and easy way. The mould is based on a flexible membrane with 21 (in height) adjustable points.

1: laser projection for the placement of edges and brackets (flat surface)

2: casting high performance concrete (flat surface)

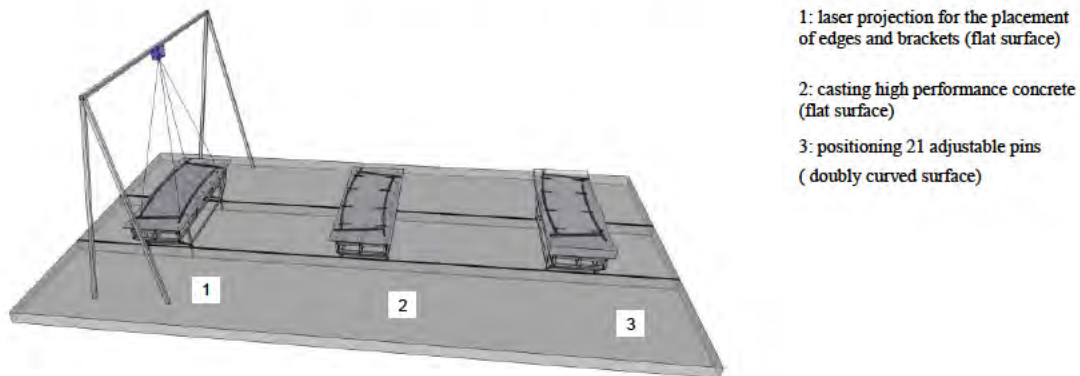3: positioning 21 adjustable pins
(doubly curved surface)

Figure 14: Production process of doubly curved concrete elements

Combining a 2D-laser and a digital drawing (DXF) makes it possible to place all edges and fixing points on the right position with low tolerances. All parts of the mould are flexible and can be re-used to create new panels with different shapes.

Figure 15, 16: Laser projection for the placement of edges and brackets

The concrete is poured in a horizontal position of the mould. The high performance concrete makes it possible to curve the panel when the concrete is still in its hardening process. The concrete is reinforced using small glass fibres to make sure all different shapes can be made.

Figure 17, 18, 19: Adjustable pin construction flexible mould

The final curvature of the panel is shown on a 2D production drawing. The drawing shows all 21 height dimensions of the adjustable pins. A measuring tool and hydraulic system is used to set out every pin to the correct height.
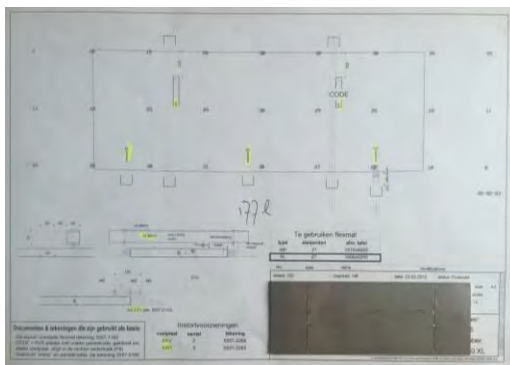

Figure 20: Production drawing   Figure 21: GFRC curved panels

5. Building surveying (LBA Bouw B.V.)

The exported CSV file from the 3D-modelling software contains the Name, X-, Y- and Z-coordinates of each point in meters. If the data is formatted as example Figure 22, it can directly be imported into the Total Station.

To make sure the GFRC panels will fit on the S/S hanger bolts, the substructure needs to be set to the correct 3D position.

```
DS8A_E,113.135,-51.257,39.74,
DS8A_S,113.135,-51.257,39.84,
DS8B_E,113.135,-51.057,39.74,
DS8B_S,113.135,-51.057,39.84,
DS9A_E,113.135,-53.356,39.74,
DS9A_S,113.135,-53.356,39.84,
DS9B_E,113.135,-53.156,39.74,
DS9B_S,113.135,-53.156,39.84,
```
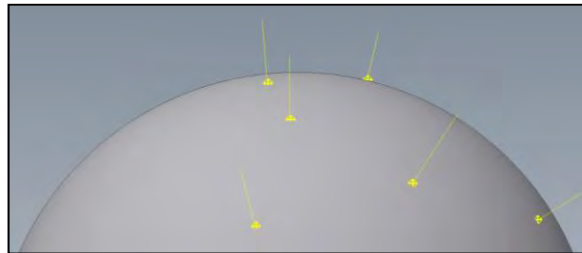
Figure 22: Text file input Total Station

Figure 23: Normal vectors on 3D surface

5.1 Positioning of hardwood blocks

Two normal vectors (Figure 23) are needed for the position of one hardwood block.

The Total Station is equipped with software to define a vector (line) from a start point (S) to an end point (E). Using this method the distance from the tip of the detail pole (with a mounted 360° prism) to the defined vector can be measured continuously.

The surveyor will move the detail pole along the defined vector until he hits the structural roof. The coordinates of this measured point (SO) will then be stored. (Figure 24)
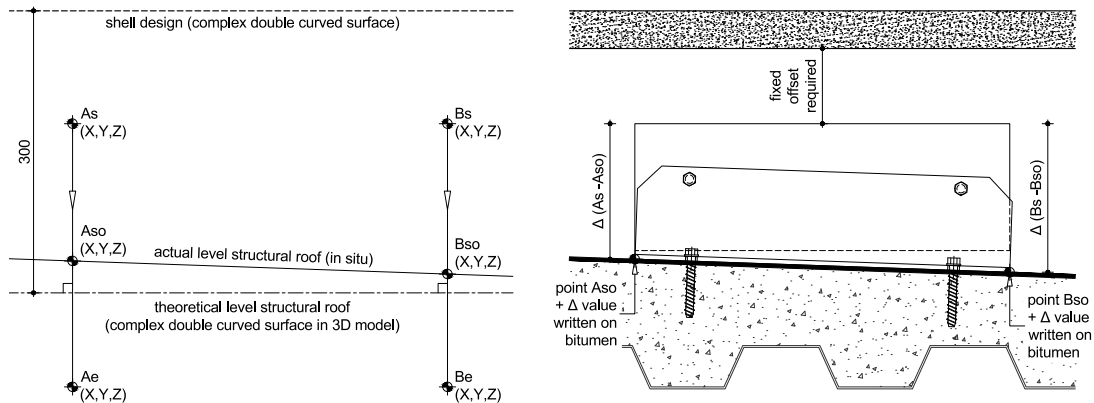

Figure 24: Normal vectors used for positioning of a hardwood block

Figure 25: Position and height for installation of hardwood block on structural roof

Additional software calculates the distance (delta-value) between points S and SO, which is written down on the roof. (Figure 25)

5.2 Positioning of S/S hanger bolts

After applying the roof insulation and waterproofing, the surveyor uses the same vector approach for setting out the positions of the S/S hanger bolts, on top of the aluminium hat. (Figure 26)

Figure 27 illustrates how the steel brackets of the GFRC panel fit on the installed hanger bolts.

Figure 26: Position hanger bolts on top of hardwood block (covered with aluminium hat)

Figure 27: Assembly of GFRC panel with hanger bolts

6. Conclusion

In order for a digital chain of information to work in a project it requires good common agreements on the data exchange (naming, formats, etc) between all parties. Next to these technical requirements there must also be trust between parties on the data that is exchanged. This is usually built-up in long-term relationships with different projects that have been done together. Lastly, one has to overcome the contractual borders of responsibility and liability which is the hardest to let loose.
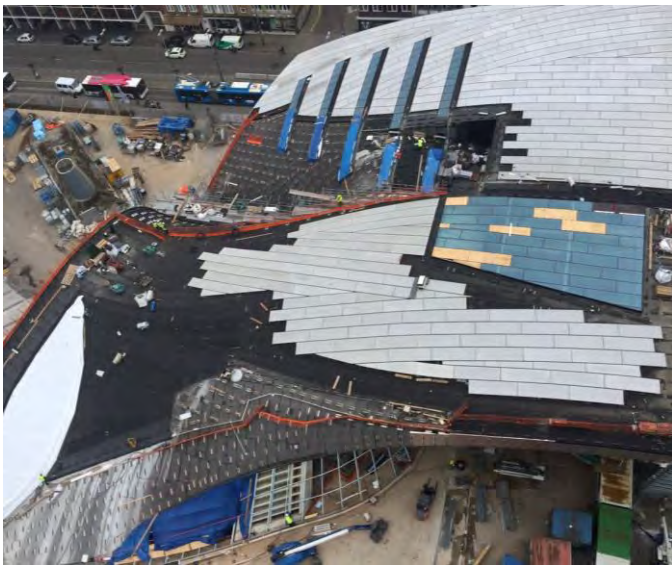

Figure 28 – status in April 2015

In this example some parties already worked together on other projects and some parties were new to each other. During the process the trust was established with tests on the data exchange that were confirming the link between the different software packages or required alterations in the process. Full scale prototypes were produced to evaluate the visual result but also used as a real-world test of all the interfaces between data and production.

As a result the process can be called a digital information chain as none of the data in the chain was altered or changed but was rather, through additional engineering, enriched with further information.

There are still a number of improvements to be found in a process like this. Contractual hurdles are in the minds of many companies which make them fall back into the traditional habit of locking off communication after the initial exchange of information. What we have learned is that in a process of a digital chain all parties have to communicate closely during the whole process to gain the most out of the efficiency that can be brought to the project.

Acknowledgement

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References

[1] Coenders, J.L. and Dingsté A. The NSP Arnhem Public Transport Terminal Qilin Zhang, Lianping Yang, and Yuyin Hu, editors, Spatial Structures – Temporary and Permanent – Extended Abstracts - International Symposium of the International Association for Shell and Spatial Structures (IASS), Shanghai, China, November 8-12, 2010, pages 549–550.

[2] Van Veen M., Hoppermann M., Dingsté A., Innovations in the design and production of a free form shell structure - The building of the public transport terminal Arnhem, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015, Amsterdam Future Visions