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The Frankfurt Zeil Grid Shell

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Abstract

Recently the MyZeil shopping mall as a part of the PalaisQuartier has been opened to the public in the very center of Frankfurt in Germany. It consists of two high-rises including one office tower, one hotel tower and a five-storey retail building. The core part is the MyZeil with around 78.000m² gross storey area designed by the Italian architect Massimiliano Fuksas. The building agglomeration is covered by a 13500m² triangulated glass/steel roof and rhombus shaped facades.

The following article will highlight the special approach and procedures which have been applied during design, fabrication and installation of the roof and for its maintenance.

First the overall geometry was optimized by close coordination with the architect in order to fulfil the aesthetic as well as the structural requirements. At this stage Rhino-files were used to communicate the numerous alternatives of the roof geometry between the architect and the engineer. Much effort was put into the meshing of the grid on the heavily curved 3D surface. Special tools, had to be developed to produce a net according to the flow of forces.

In the next step the nodal connectors had to be designed in a way that they could be adjusted to all geometries and to all loading conditions. For the structural analysis of the members and nodes of the grid the same geometric data model was used that served as a basis for the shop drawings and the fabrication of the hollow box steel members and its nodal connectors.

The structure was then erected by welding the members on site which allowed to meet the specified tolerances.

At the end, a highly optimized structure was achieved which not only marks the state of the art for grid shells but which is also an architectural landmark in the city of Frankfurt.

Keywords: free-form, geometry, data flow, design to production, form finding, optimization, glass steel structure, computer aided manufacturing

1. Introduction

Shopping malls are often understood as iconic buildings by modern architecture with expressive design and eye-catching shape. The relatively new design approach is often based on free form geometries which are encouraged by recently developed easy to handle 3d-software tools being more and more introduced into the planning process.

The role of the engineer is conceived as that of a mediator between the aesthetic ambitions of the architect, the budget of the client and the technical capabilities of the contractor. From the very early stages of form finding to the assembly on site, a consistent design process is absolutely necessary to achieve high quality free formed structures.

Computer controlled fabrication methods allow for structures, which would not have been possible a few years ago. But how does one transfer 3D geometries into a load bearing structure without loosing the architectural vision of smoothly shaped building envelopes?

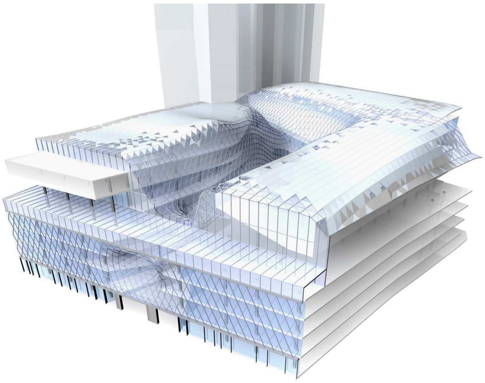

Figure 1: Persepctive of retail building with roof

2. Concept to erection

For 3D-shaped buildings, grid shells are often used as a structural system. In the early days of grid shells, the limitations of fabrication were very strict. The number of members with different lengths or nodes with different angles had to be reduced to a minimum. The methods of numerical analysis were also limited. Only geometries and meshes could be used, for which methods of structural analysis existed. These technical restrictions limited the options for grid shells and led to certain standard types of construction systems and architectural forms for domes and other 3D-structures, which were used repeatedly.

Neither fabrication nor structural analysis causes limitations for the design of free formed systems anymore. Due to Computer Aided Manufacturing (CAM) nearly every 3D-geometry can be built. However, many examples can be found where an elegant 3D-shape was not transferred into a built structure accordingly. Irregular grids and rough construction details affect the structural integrity and the elegance of the architectural idea. The reason is often that the architectural design on one hand and the technical realization on the other are considered as two different tasks carried out subsequently by different people with different approaches and tools. While architects often work with 3D modelling tools, engineers use finite element analysis software with an interface to CAD applications. Thus even on a technical level, the communication between the aesthetic and the structural design is often difficult.

To achieve an optimal solution for a grid shell, a continuous process of engineering from the very first architectural idea to the assembly on site is necessary. This process, the digital chain, basically consists of the following steps:

- Optimizing shape and all-over geometry
- Meshing
- Design of nodal connectors
- Structural analysis
- Production and Erection

The meshing of the grid, in particular, is a new design step which requires new tools. All steps need to be carried out carefully to achieve an optimal solution. The project MyZeil is an excellent example to this consistent process of design.

2.1. Optimizing shape and over-all geometry

Like a carpet, a grid shell covers the concrete slab levels. Figure 2 shows the first architectural vision of the geometry that we received as a ‘Rhino’ file. The geometry consists of flat areas, which are connected by sharply bent edges. The ‘canyon’ in the centre, which is above the shopping mall, is supposed to be column free for the comfort of the pedestrians. In the first design step, the 3D shape was optimized in two ways. First, the two horns, which were initially only aesthetic elements, were used as large columns, i.e. as structural elements. One is supported on the ground level and the other by the façade structure. Thereafter, the sharp edges were smoothed to allow a flow of forces which enables shell-behaviour and reduces the bending moments in the steel members. Figure 3

By doing so, a column free shopping-mall was achieved. The flat zones above the top levels are supported by columns with a regular spacing. At this stage of the design intense discussion between architects and engineers about geometries and shapes took place via the exchange of ‘Rhino’ files.

Figure 2: Original shape

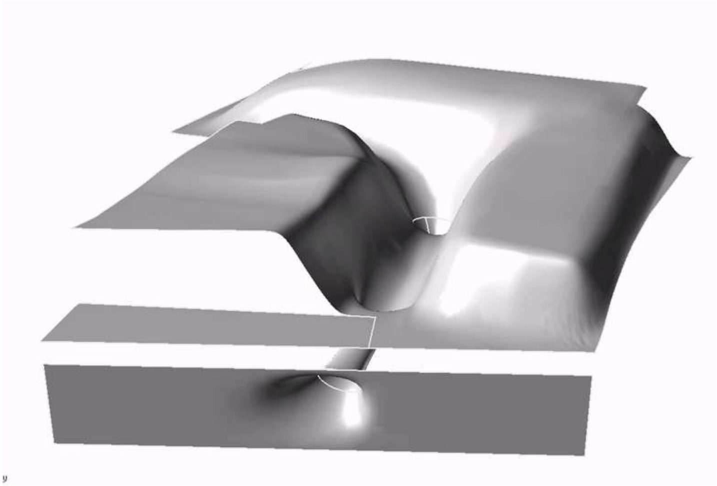

Figure 3: Optimized shape

2.2. Geometry meshing

In the next design step, the 3D-shape had to be transferred into a structural grid. Due to the complex geometry a simple projection method could not be used in this case. Standardized methods and tools do not exist for this task. Often, automatic mesh generators from FE-analysis- or 3D modelling software are used. However, they usually do not lead to satisfying results. These meshing tools start from the boundaries and connect separately generated zones, which leads to irregular meshes in the centre. This isn’t satisfying from neither an aesthetical nor structural point of view. Figure 4

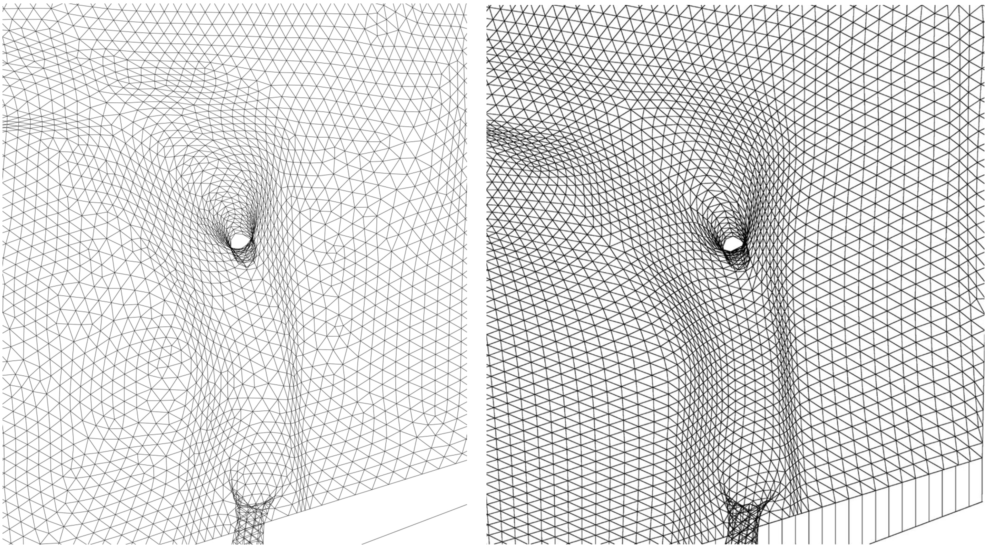

Figure 4: automatically generated mesh (left) and result with scripted tools (right)

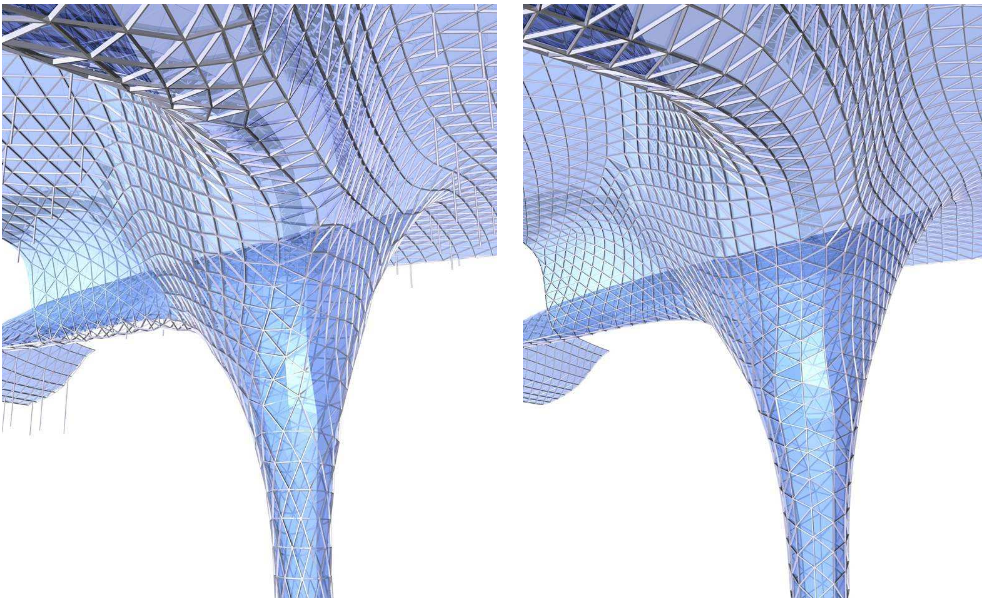

Figure 5: interior view of autogenerated mesh (left) and result with scripted tools (right)

To achieve an orientation of the members which satisfies aesthetic as well as structural requirements ‘lines of orientation’ as well as connection points for the vertical façade were defined. These were used as starting points or as boundary conditions for the mesh generation. Figure 6

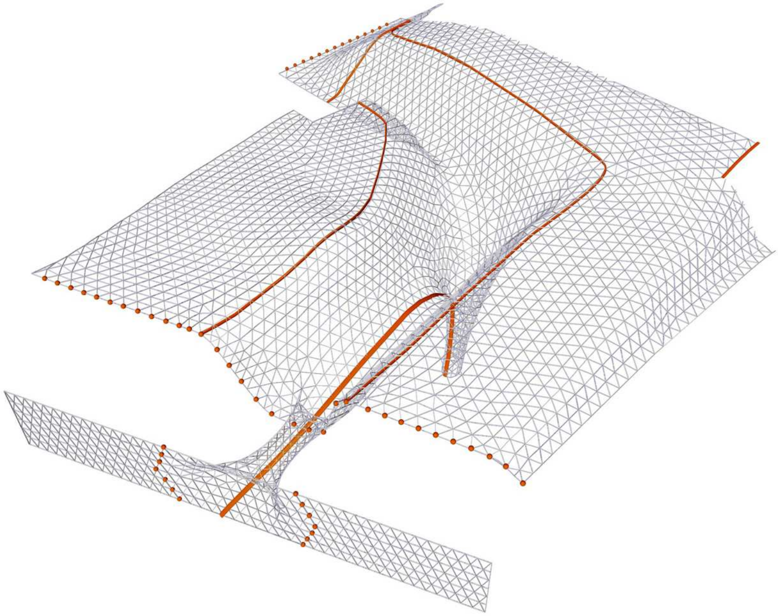

Figure 6: geometrical constraints and lines of orientation

Next, the shape was divided in ‘mega-triangles’, which define the position of the 7-member nodes, which are unavoidable for such kind of geometries with strong boundary conditions. Within these ‘mega-triangles’ continuous nets with smaller triangles and 6-member nodes were generated. This procedure is similar to the one used by Buckminster Fuller for his geodetic domes. However, some manual adjustment was still needed. After several intermediate steps the grid in Figure 5 (right) was achieved, which served as a data-model for structural analysis and the shop drawings as well as for fabrication. The average member length is 2.30 m.

2.4. Structural analysis

The final grid geometry was transferred into a finite element model using transformation scripts. The orientation of each profile could be adjusted normal to the grid surface within the same step. Figure 7

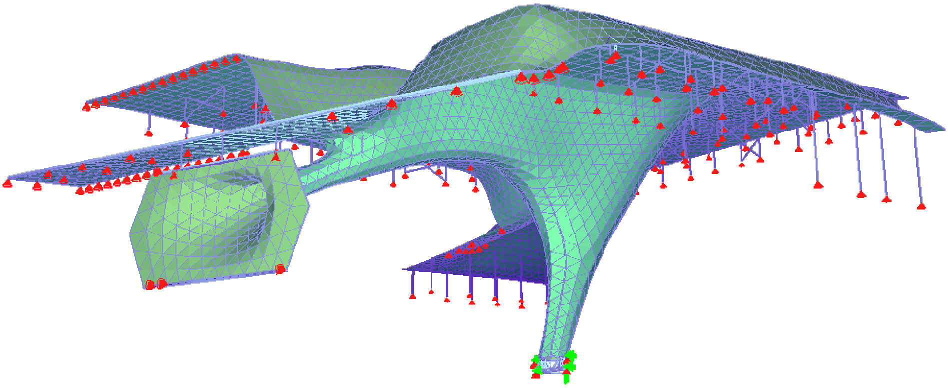

Figure 7: Finite element model of roof structure

Wind and snow loads were investigated based on the complex geometry of the roof structure by a university institute (IFI FH Aachen).

A detailed wind tunnel test has been undertaken to determine the distribution of wind loads. The PalaisQuartier project and its urban surroundings have been included in the wind tunnel model (scale 1:500). Wind pressure results were measured for 12 different wind directions. Due to the adjacent high-rise buildings areas of the roof structure were detected where wind pressure is concentrated.

Furthermore, a snow load report has been carried out by the same institute locating and quantifying areas of snow drifts and quantifying them. Extremely inclined areas such as the canyon walls lead to snow concentration at the lower areas such as the canyon bottom or the base of the large column. Without additional technique such as snow guards especially the column base would have to bear a height of 12 m of snow slipped from the canyon walls.

Finally, around 100 linear and non-linear load combinations have been calculated (using 3rd order theory)in order to detect the maximum design stresses of each roof member. The shell structure consists of areas which are mainly under compression (e.g. large column) as well as those mainly under tension (e.g. canyon walls). For some regions linear calculation leads to conservative results while in others non-linear effects have to be considered. Each section has been optimized to its worst load combination.

2.3. Design of nodal connectors

The transformation of the data model into a built structure depends very much on the experience of the contractor and the means of fabrication. There is no standardized solution for the nodal points of the grid. In contrast to the roof for the trade fair in Milano, which was also designed by Massimilano Fuksas, the architect wanted an aesthetically unobtrusive detail for the nodal connector.

For this structure the contractor (Waagner Biro, Vienna, Austria) proposed a welded connection for the node, which is based on the experience that he had gained for the roof over the courtyard of the British museum in London Figure 8. The beam members are welded to a central ‘star’, which is burned out of a thick steel plate. However, due to the complex geometry about 10% of all nodes are fabricated as a compact steel block. The node geometry is developed in a way that the centre lines on top of the steel members meet in the node (the same holds for the Westfield project in London). The members are welded hollow box sections with an average size of 120x 60 mm. The thicknesses of the plates are adapted to the respective loading conditions.

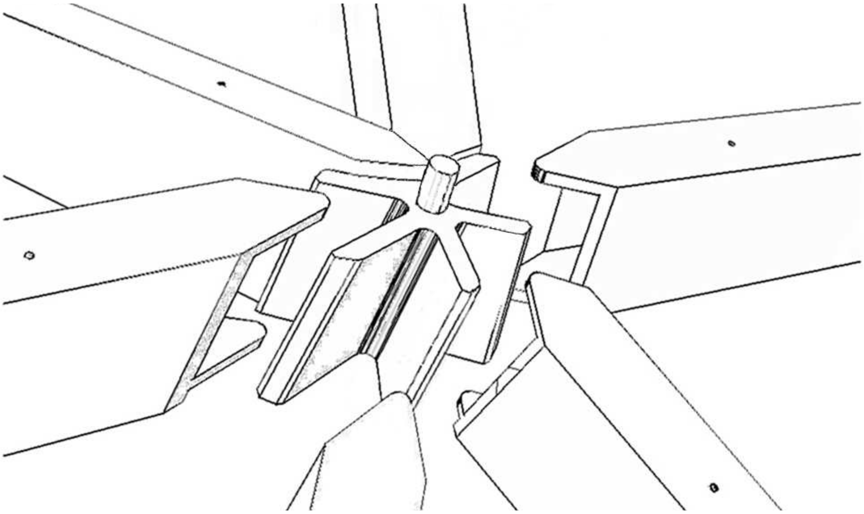

Figure 8: nodal connector of MyZeil (Waagner Biro)

For the structural analysis of the node plates the individual stress condition at each position is considered. Anyway, their complex geometry has been simplified to a perfect planar hexagonal system which allowed for a generalized calculation method. Since vertical and torsional rotation angles of the beams have an important influence on the node balance and on the stress distribution additional coefficients are introduced to adjust the simplified results. Finite element models of all individual node geometries could be avoided by these simplifications. However, some major geometrical cases have been investigated using FE models to determine the coefficients and for a better understanding of the distribution of forces. Figure 9, Figure 10

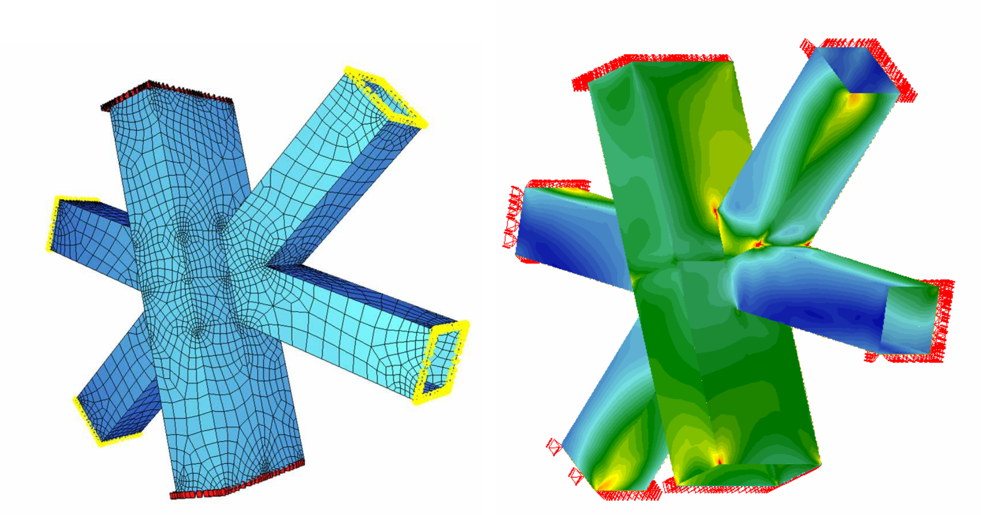

Figure 9: Finite element model of node with eccentrically connected diagonals

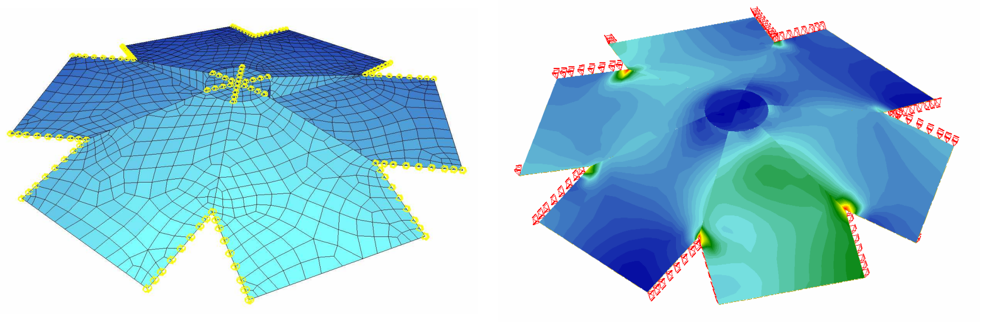

Figure 10: Finite element model of standard roof node (upper flange)

Within the generalized calculation method only the flanges of each beam connected to the node are considered to transfer internal forces. They are fixed to each other (upper flange) or to the central ‘star’ (lower flange) by full penetration butt welds. The webs are neglected for the load transfer and fixed by nominal fillet welds.

2.5. Production and Erection

The gridshell is divided into manageable pieces forming ladders. The ladders were prefabricated in the workshop. On site they were lifted into position and connected to the adjacent structure by inserting and welding the lose members. A spatial scaffolding supported the structure during erection and allowed to adjust the position of nodes according to the required tolerances. Figure 11, Figure 12

Figure 11: grid during construction

Figure 12: grid during construction

2.6. Cleaning concept

Depending on the location and orientation of each glazed surface of the roof structure convenient cleaning methods have been developed. For vertical surfaces such as vertical facades a portable hoisting platform will be used. Horizontal or inclined surfaces of the canyon roof will be cleaned by a special ‘Cat Wash’ vehicle with brushes operated by remote-control. Figure 13

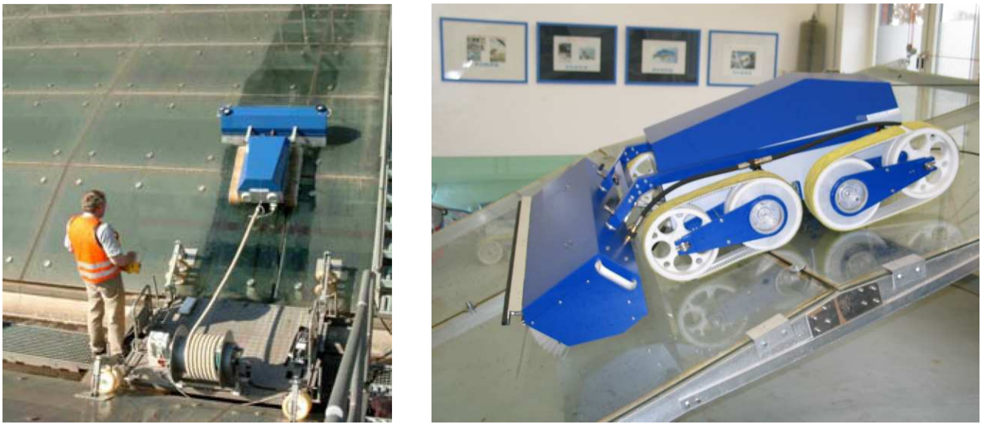

Figure 13: CatWash façade cleaning vehicle (pictures by TAW)

The large glazed column is difficult to clean by common methods. Therefore, an element called 'air-beam' has been developed by TAW. Hidden below the bottom plate of the large column it will be blown up for the cleaning process. To control the beam it is fixed at three points in the upper part of the roof, and rotating brushes move up and down. Figure 14

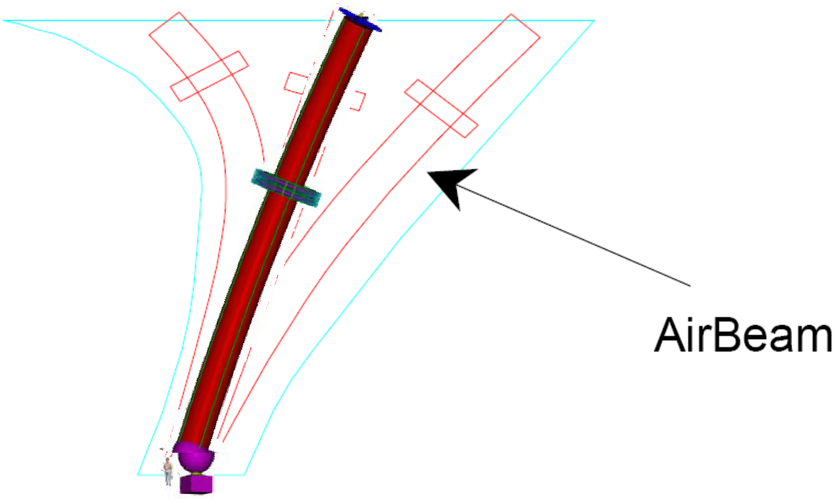

Figure 14: AirBeam cleaning system for large glazed column (figure by TAW)

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