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Design, optimisation and construction of the façade of the KTM Motohall

The KTM Motohall in Mattighofen (Austria) was commissioned by the KTM Motohall GmbH and designed by the architectural firms HOFBAUER LIEBMANN WIMMESBERGER Architekten ZT GmbH, and X ARCHITEKTEN ZT GmbH. Completed in 2019, it now accommodates exhibitions that highlight the history of the Austrian motorcycle and sports car manufacturer KTM AG and aims to communicate the brand's identity to a broader audience [1].
One of the building's most prominent features is the façade construction, consisting of three elliptical windings between 5 and 7.5 m in height that hover around the concrete core. The lower winding contains a sloped observation deck that guides visitors all the way around the core of the building. The two upper windings are skewed against each other and at certain places they cantilever up to 8 m. The outside of each winding is clad with perforated aluminium sheets, while the entire load-bearing substructure is made of steel.
Only the façade structure will be discussed in this paper. It was realised in collaboration between the architects (see above), Werkraum Ingenieure ZT GmbH, who managed the geometric development and structural planning as referred to below, and Unger Stahlbau Ges.m.b.H., who orchestrated the steel construction. The complexity of this architectural vision required a seamless transition between design, geometry, structural engineering, and construction.

1 Objectives

The structural planning and construction of the façade for the KTM Motohall posed several interesting challenges that required effective work by all parties. In this paper only a handful of these challenges are selected and discussed in greater detail:

- Despite the intricate geometries of the windings one of the objectives was to generate a coherent structure


Source: Werkraum Ingenieure

Fig. 1 KTM Motohall view from side/rear.

that could be realised using standard connections and parts (s. Chap. 2).

- At first glance it seems unavoidable that some rods would intersect within the construction of the two upper windings in a very inconvenient manner that would require intense detailed planning. By utilising parametric modelling and optimisation algorithms it was possible to avoid such intersections entirely (s. Chap. 3).
- The engineers set out to provide a delicate structural solution that was efficient in fabrication and assembly. This was achieved by deploying steel's unique material properties (s. Chap. 4).
- When producing architecture today it may be considered our moral obligation to address sustainability related issues (s. Chap. 5).
- It is implicit that the global aim was to conceive a design that supports the vision of the architects and the client in a conceptually strong and consistent way.

2 Geometric standardisation

In a purely geometrical sense, the upper part of the building including the metal façade consists of three elliptical cylinders: inner winding W_{IN}, outer winding W_{OUT} and the concrete core of the building C (s. Fig. 2). They are all right cylindrical surfaces – meaning that their generating line (generatrix) is orthogonal to their base. None of the three cylinders are concentric to one another. Furthermore, W_{OUT} does not even share a plane with the other two cylinders but is skewed by approximately 2°. Clearly, even these small irregularities make the design quite intricate.

The objective was to develop a strategy for translating the geometry into a structure that captures the architectural idea in a coherent way whilst retaining a reasonable degree of standardisation. The solution was developed through parametric modelling in Grasshopper – a versatile plugin for the CAD software Rhino (Note: Rhino and Grasshopper are developed by Robert McNeel & Associates). This allowed the architects and structural planners to generate and examine different variations much more efficiently by merely adjusting a few parameters.

The algorithmic strategy that was developed also works for three nonelliptical cylinder surfaces that are all skewed towards one another. The following text therefore describes the approach in the most general form.

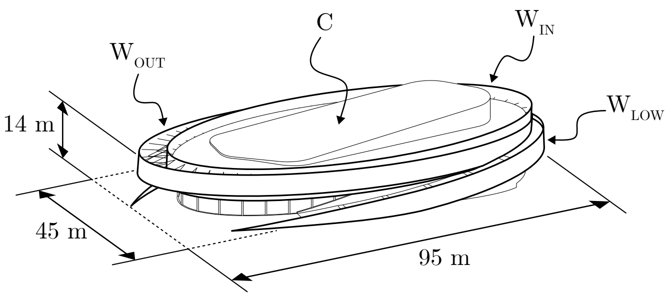

Fig. 2 Overview of the KTM Motohall including all parts of the façade construction.

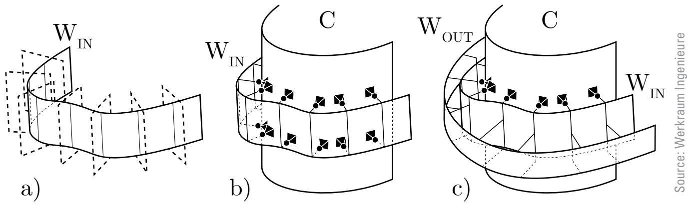

Fig. 3 Geometric construction of the façade, a) W_{IN} is divided into equal sections, b) W_{IN} and C are connected by planar frames orthogonal to W_{IN}, c) the frames are extended within the same plane to connect W_{OUT} to W_{IN}.

First the inner winding W_{IN} is divided into sections of equal length (s. Fig. 3a). Since all the windings are clad with perforated aluminium sheets, the size of these sections is determined by the maximum width of sheets that can be manufactured. The seams between these sheets act as natural lines of intersections for cantilevering members that connect the outer winding W_{OUT}, the inner winding W_{IN}, and the concrete core C to one another. Those members are executed as frames and, depending on their structural purpose, some of them may be braced.

Every frame is planar and orthogonal to W_{IN}. It is easy to see that therefore the frames meet C at varying angles. The connection is achieved by cutting the rods to the right angles and bolting them to the concrete, utilizing end plates (s. Fig. 3b).

To connect the remaining outer winding W_{OUT} to the rest of the structure, first of all the planes of the frames are extended outwards and intersected with W_{IN} – their intersections are planar curves. As W_{OUT} is skewed against the inner winding W_{IN} there may be some variations in height that have to be considered. Finally, points on these intersection curves are connected to points on the generatrix of W_{IN}, resulting in a second outer layer of planar frames (s. Fig. 3c).

Fig. 4 shows sections through the planes of the frames in different exemplary situations. Note how the skewing and height differences are compensated in a consistent manner.

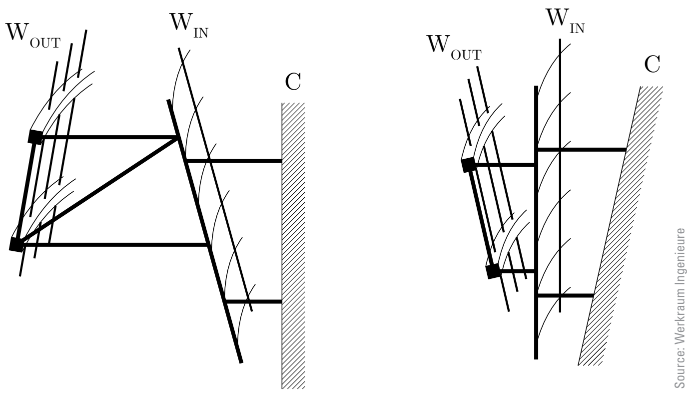

Fig. 4 Schematic sections through the planes of the frames for different situations; some frames are braced.

3 Geometric optimisation of the outer winding

The function of the outer frames is to carry the rods that comprise the upper and lower ellipses for the outer winding W_{OUT}. To clad the surface of the winding with metal sheets an additional construction is required. This substructure consists of rods between the two ellipses that represent the generatrices of the cylinder surface (s. Fig. 5).

To mount the aluminium sheets efficiently it is desirable that these generatrices be evenly spaced. But since the frames intersect the outer winding at irregular points and occupy the same spatial layer as the generatrices, inconvenient intersections between the frames and generatrices are expected and need to be addressed.

One obvious approach would be to invest resources in designing individual steel joints for each intersection. But sometimes the best solution is not needing a solution in the first place! So, the following question arose: is there a way to orient the frames and generatrices of the outer winding W_{OUT} so that such intersections are avoided entirely, while still retaining regular divisions along each ellipse (s. Fig. 6)?

Although all the values within the parametric model can be easily manipulated, it quickly becomes obvious that it is virtually impossible to find such a solution "by hand". Here Grasshopper's built-in optimisation solvers can help: The software offers an evolutionary solver as well as a solver that utilizes simulated annealing. The primary goal is to detect whether such a solution exists in the first place, rather than refining a solution. Therefore, the simulated annealing solver was used in the optimisation process [2].

The global position of frames along the inner winding W_{IN} as well as the position and the regular spacing of the generatrices of the outer winding W_{OUT} were the parameters that the solver was able to manipulate. The fitness target was to maximise the smallest distance between a frame and its neighbouring generatrices. If this fitness

Fig. 5 Construction of the upper windings with frames and generatrices.

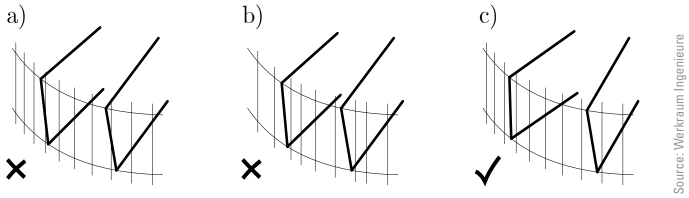

Fig. 6 Different situations for the positions of generatrices and frames on W_{OUT}, a) the frames intersect the generatrices, b) there are no intersections but the generatrices are not evenly spaced, c) the distance between the generatrices is even and there are no intersections.

value exceeds a certain practical threshold, then the problem could be considered solved.

The first optimisation runs did not yield promising results and so the restrictions were loosened: The circumference of the outer ellipse was divided into two sections with each of them having an even spacing of generatrices without necessarily having the same spacing. This structure still retains a high degree of standardisation whilst opening up additional scope for optimisation. So, in the consecutive runs the solver was also able to determine the start and endpoints of the two sections as well as the spacing of the generatrices within those two sections.

This approach was successful and produced the desired result: Not a single intersection had to be dealt with! The optimised Rhino model could be directly exported to the structural analysis software RFEM (s. Chap. 4) (Note: RFEM is developed by Dlubal Software GmbH).

4 Structural design

The target of the previous chapters (Chaps. 2 and 3) was to provide the prerequisites for the simplest possible fabrication and assembly of the geometrically complex parts. Consequently, the structural design adopted the same objective. All structural elements of the façade were made in steel. For the design, the ellipses of all three windings were comprised of the sectionally best approximating circular arcs.

The entire structural analysis was performed with the finite element software RFEM.

The following section discusses the two upper windings W_{IN} and W_{OUT} separate from the lower winding W_{LOW}.

4.1 Upper windings W_{IN} and W_{OUT}

Due to the displaced and twisted position in relation to the concrete core, cantilevers of up to 8 m are created. To achieve the impression that the outer winding W_{OUT} floats, horizontal bracing struts should be avoided wherever possible.

The dominant load case for rigid circumferential bearing of the elliptical rings is temperature, or, more precisely,

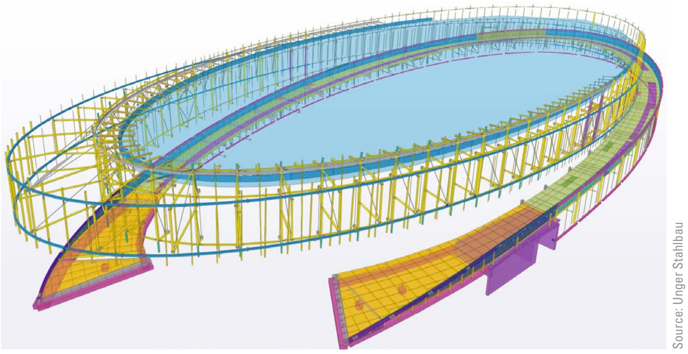

Fig. 7 Screenshot of the façade model in the construction software Tekla (Note: Tekla is developed by Trimble Solutions Germany).

the temperature difference between the concrete core and the external steel structure. Not only do compressive forces arise in the circumferential curved profiles of the substructure when the steel structure expands in an impeded manner, but, above all, the horizontal anchorage forces in the concrete body would increase considerably as a result.

To address both the structural and architectural requirements the windings are divided into two segments that function slightly differently: segment A consists of the widely cantilevering frames above the entrance, while segment B is the remaining part where the windings sit "more tightly" around the concrete core.

For the lateral stabilization of segment A, horizontal force frame-abutment structures were arranged at the start and end of segment A around the circumference, where the windings are relatively close to the concrete core (s. Fig. 8).

These frame-abutment structures form the fixed points for the horizontal forces that occur as a result of wind loads or temperature constraints. They are comprised of horizontal frames that can absorb the load level of wind forces just within the elastic range of the steel's stress-strain curve. To limit the forces due to temperature constraints the frames are tuned in such a way that they deform plastically under loads any higher than the wind loads. In this way, the targeted formation of a yield plateau – an essential property of the material steel – was efficiently used to limit constraint forces.

In segment B thanks to the small cantilever length the lateral stabilization of the substructure could be realized by direct clamping into the concrete core. The elliptical rings are equipped with axial movement joints to limit the constraint forces resulting from temperature. The approach of minimizing constraint forces also kept anchorage forces within a range that allowed wide sections to have simple dowel solutions.

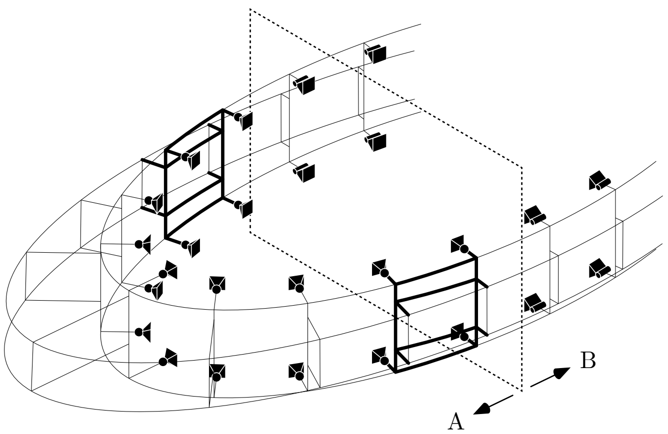

Fig. 8 Schematic drawing of the upper windings with frame-abutment structures in segment A.

4.2 Winding W_{LOW} with ramp

The winding W_{LOW} is part of the ramp's substructure. Here the horizontal stabilization of the frame axes is given by the ramps themselves in any sections. Analogous to the segment B in the upper windings, the elliptical rings of the ramp contain axial movement joints to limit any constraining forces. Therefore, here, too, the connection of the frames to the concrete core required just a simple solution using dowels.

5 Sustainability

Currently, between 97 % and 99 % of all scrap steel is reused or recycled [3]. This makes steel one of the most sustainable material options for building delicate structures like the façade of the KTM Motohall. As early as the conceptualisation phase, the design of the façade kept in mind the option of dismantling it at some time in the future – the bolted connections simplify this and allow the individual steel members to be transported to a new place of use or to be recycled.

6 Conclusion

Easy-to-handle parametric modelling software like Rhino/Grasshopper has been around for over a decade and resources as well as extension plug-ins are widely available [4]. Despite the obvious benefits of parametric modelling, such as the ability to optimise geometries, it still does not seem to be a go-to tool for architects or structural engineers. The KTM Motohall showcases the possibilities of a

Fig. 9 Details of the upper windings.

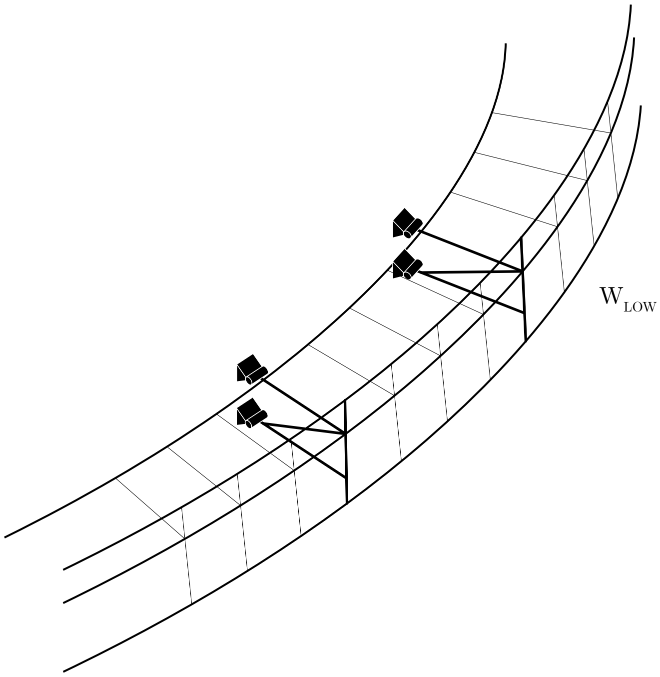

Fig. 10 Schematic drawing of W_{LOW} containing the ramp.

parametric approach by solving problems which, using traditional CAD software would have been tedious at best and impossible at worst – let alone pen and paper!

Furthermore, the façade construction implements steel's distinctive material properties by not only thinking in terms of its Young's modulus, but by also utilising the plastic range in steel's well explored stress-strain curve.

The KTM Motohall demonstrates how complex geometries can be efficiently translated into structures that are optimised with respect to fabrication and assembly, whilst supporting the architectural vision without the need for compromise.

References

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