The 36,000-square-foot railway station transfer hall is the centerpiece of the Arnhem Master Plan, a large urban plan development composed of office space, shops, housing units and other structures in the Netherlands. The transfer hall includes ticket sales and waiting areas for trains, taxis and buses, as well as retail shops and restaurants. The organic design created by UNStudio consists of a series of flowing curves. The original plan was to build the structure from concrete, but when the complex curves made concrete infeasible, designers turned to steel. Instead of using traditional steel construction with a load-bearing truss, the design and engineering team decided to use a method pioneered in the shipbuilding industry: a curved steel-plate interior with an attached web of frames for the load-bearing structure. The steel structure was divided into 150 smaller blocks. These building blocks were built at construction yards and assembled on-site.

Central Industry Group (CIG), a company that got its start in the shipbuilding industry but now also serves the architectural market, was selected to build the unique structure. Because the construction method has been used only a few times in public buildings, extensive calculations were required to prove the global and local strength, and the stiffness and stability of the design. Because the geometry is so complex, it would not have been practical to perform the required calculations using traditional manual structural analysis methods within the project schedule. In fact, it is difficult to estimate how long manual analysis would have taken, but CIG's familiarity with the ANSYS Mechanical Parametric Design Language (APDL) made it possible to perform the analysis using automated methods in a relatively short period of time.

**CREATING A STRUCTURAL MODEL**

CIG engineers began by creating a full model of the load-bearing structure in Rhinoceros® 3-D computer aided design (CAD) software using the inner shape of the building as provided by the architect. No simplifications were made to the actual shape. Rhinoceros cannot export thicknesses or materials, so if the entire model had been exported, thicknesses and materials would have to be recreated manually. To avoid

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Simulation software flexibility drastically reduced the time to perform structural analysis of a railway station with complex curves. The innovative construction method required extensive structural calculations that were performed with ANSYS simulation software to automate the engineering of this award-winning structure.
this, CIG engineers built the Rhinoceros model as a series of
subfiles, with each having a constant thickness and a single
material. The structure primarily consists of AH36 steel. They
used a Rhinoceros script to separately export each subfile in the
SAT format. Then they used an APDL script to import each sub-
file into ANSYS Mechanical while capturing the thicknesses and
material properties of each layer. Each subfile was converted to
an ANSYS Mechanical group so that each section of the model
could easily be made visible or hidden. The model consists of
SHELL281, SHELL132, BEAM189 and COMBIN14 elements.

GLOBAL ANALYSIS

Engineers then performed a global strength/stiffness/stability
analysis to first demonstrate that the structure could feasibly
be built using this construction method. The team selected 19
different loading conditions, including gravity, snow, wind and
ambient temperature loading. These loading conditions were
combined into 75 load combinations. Engineers used another
APDL script to perform 75 simulations and search the results for
the load combination that generated the highest stress in each
element. Then the script plotted the highest stresses for each
element onto a single image of the structure so that it was pos-
sible to see hot spots at a glance. The script determined the load
combination number that generated the highest stress on each
element onto the structure. This method enabled engineers to
understand the performance of the structure, and also saved
time when presenting results to the customer. The hot spots
were further analyzed in submodels using the prescribed trans-
lations and rotations at the boundaries of the submodel obtained
from the global model. The submodels included more construc-
tion details and a finer mesh.

Residual stresses due to this block assembly and reaction
forces on the temporary supports were determined by simulating
the on-site block-building process of the roof structure using the
global model. The residual stresses were used to define margins
for the local stability calculations of the individual structural
items. The reaction forces were used to design the temporary
support structure.

Global linear and nonlinear buckling analyses were per-
formed to determine the global stability of the structure. The
global stiffness model was also used to determine deflection of
the structure in areas where it adjoins glass panels. The max-
imum deflection of about 5 cm, determined using simulation,
was accommodated in the construction with a joint that creates
a small gap between steel and glass.

MODELING SUPPORT STRUCTURE VARIANCES

The station hall is built on top of different concrete struc-
tures, such as parking garages. The vertical stiffness of these
structures and the soil below was incorporated into the model
with spring elements. The concrete structure was modeled by
its contractor using a different finite element software package.
For each of the 19 loading conditions, engineers iterated between the steel ANSYS model and concrete structural analysis while changing the prescribed horizontal translations at the supports until the horizontal movement and reaction forces for both models were equal.

An APDL script was created with a range of vertical spring constants in an array table to iterate with different spring values. This enabled the ANSYS model to determine effects of variances in support structure properties. For example, if one support was 100 percent stiffer than the specification, how would that affect stresses in the steel structure and influence the reaction forces in the supports? This analysis was used to provide the builder of the concrete parking structure with construction constraints.

Another APDL script was used to plot differences between the standard stiffness configuration and the stiffness variants onto the structure to determine the margin of safety required to account for variances in the support structure. This margin is used for calculations of the supports and local stability calculations described in the next section.

**SIZING THE INDIVIDUAL PLATES**

Dutch and international building codes do not specify a detailed method to determine the stability of panels with complex curves, so an analysis method was developed within ANSYS Mechanical using APDL scripts.

An APDL script created submodels from the global model in areas containing highly curved and loaded areas. These submodels incorporated more detail and a refined mesh. Internal nodal forces from global analysis were used as boundary conditions to represent the stresses in the panel. The edges were simply supported in the out-of-plane direction.

When the sheet metal structure is constructed, the geometry will not perfectly match the model, so allowances needed to be made. To take into account these imperfections, a linear buckling analysis was performed on the isolated plate. The most critical calculated buckling shape was used as a starting geometry for the nonlinear analysis. The displacements of this buckling shape were scaled to match the maximum allowable imperfections from the building code. A geometrically nonlinear elastic buckling analysis with imperfections (GNIA) was performed to estimate the stress level at which the plate would fail. In the variation analysis described earlier, it was determined that stress could be 10 percent higher than predicted by analysis because of possible variations in the support structure, so the maximum allowable stress value was reduced by 10 percent. A further reduction took into account residual stresses calculated in the block-building process described earlier. This entire process was automated by an APDL script that also generated all the relevant figures, graphs and calculation data needed for client reporting.

This project demonstrates the capability of APDL to automate complex analysis processes. Using traditional manual analysis methods, this project would have taken so long that it would have exceeded the time frame of the project. APDL scripts made it possible to do the entire analysis efficiently and on a timely basis. Without simulation this structure could not have been validated and may not have been built. Using simulation to test building methods before construction allows architects to design innovative structures that would not have been possible in the past.

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