ARCHITECTURE, ENGINEERING & CONSTRUCTION

SIMULATION IN ARCHITECTURE, ENGINEERING AND CONSTRUCTION

Structural design for fabrication white paper

PRODUCT, NATURE AND LIFE IN ARCHITECTURE, ENGINEERING AND CONSTRUCTION

These are extraordinary times for civil engineering. Innovative structures such as hyper-loops, undersea hotels and made-to-order 3D-printed buildings, which were just concepts a few years ago, are no longer considered to be in the realm of fiction. These novel structures need to be designed for either transporting people through natural surroundings, protecting them from natural surroundings or allowing them to interact with natural surroundings. The commonalities that underlay these structures consist of intricate linkages between product, nature and life. The same is true for conventional civil engineering structures, including buildings, bridges, tunnels and dams. Figure 1 shows an innovative steel lattice structure, one of the Sun Valley structures constructed for Shanghai Expo 2010.

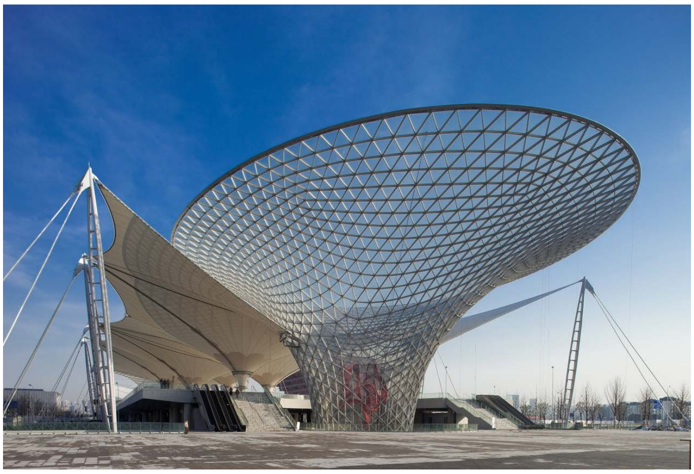

Figure 1.
A steel lattice structure constructed for Shanghai Expo 2010. Image courtesy: Shanghai Xian Dai Architectural Design Group.

We need to think about product, nature and life together, not only for creating innovative designs, but also for providing optimal functionality, ensuring safety and safeguarding sustainability for ecological well-being. Product, nature and life, therefore, need to play a conjoined role during planning for large engineering projects, such as city developments, large transportation projects, as well as dams and irrigation works. How can we include product, nature and life in the design processes for civil structures? This will need to be done through realistic simulations that take into account precise geometry and material properties, realistic representations of physical and natural processes, and rational predictions of experiences by people. Such simulations, in addition to the obvious need for ascertaining structural safety, also need to include the construction processes and sequences along with reliable estimates of construction and maintenance costs.

COMMON INDUSTRY CHALLENGES

Large construction projects often exhibit cost overruns and delays due to unforeseen events or design changes during construction. As is well known, a judicious balance between cost, time and quality needs to be maintained in any construction project in order to have the resulting product as profitable, safe and sustainable as possible.

In a construction project, the architects and structural engineers first need to come up with a conceptual design that is appropriate for the intended function of the structure. Potential structural loads need to be identified, and the conceptual design needs to be guided by the efficiency of how these loads get transmitted within the structure and distributed to the foundations. Any errors or inappropriate design choices at this stage can have significant time and cost implications on the final outcome. If the structural components are pre-fabricated, then these and the final structure need to be designed based on the ease of manufacturing the pre-fabricated parts, which can often contain specially designed new materials. Also, the transportation of these parts and the final assembly processes need to be considered. A complete study on how early design choices affect the construction process, time and costs is, therefore, necessary. Moreover, such studies need to be done quickly and also need to provide comprehensive data in order to enable architects and engineers to make proper comparisons between different conceptual designs.

Once the conceptual design has been chosen, engineers need to come up with an appropriately detailed final design. As the construction gets under way, some parts of the structure may need to be altered from their original design. In these circumstances, one needs to be able to quickly identify the implications of any structural modifications on the safety and reliability of the final product. Also, the final design needs to be updated and information on the ensuing modifications needs to be accurately and promptly passed along to the engineers at construction sites.

ROLE OF SIMULATION

In architecture, virtual or graphical simulation models can help in arriving at conceptual designs, taking into account wide ranges of criteria, such as layout, positioning, landscaping and lighting. Also, realistic rendering can be used to help make depictions lifelike, adding to their value for clients.

In engineering, virtual representations can be used to idealize structural geometrical configurations. These configurations can then be used in computational analyses to predict structural deformations and stresses resulting from applied loading and support conditions. Subsequent to such simulation analyses, the predicted data values can be visualized and examined. Based on these data values, engineers can ascertain the strength, stability and safety of the proposed structure, and can then finalize the structural design.

In construction, the finalized design is then used for material estimation and ordering, planning the construction sequence and managing the construction process using appropriate simulation tools.

As one can see, simulation helps in all three phases of any civil engineering project—conceptual and architectural design, engineering design and construction. Although individual tools are available to simulate these three phases separately, the use of such tools may result in potential loss of information when passed between different phases of the project. Civil engineering projects, hence, need simulation tools that seamlessly connect the architecture, engineering and construction phases. One such simulation tool is available from Dassault Systèmes.

The Structure Design for Fabrication process on the **3D**EXPERIENCE® platform from Dassault Systèmes has been specifically developed to provide engineers and architects with a unified capability to virtually represent conceptual designs, perform engineering analyses, analyze construction sequences and manage construction projects all together, while keeping track of individual components. It provides a unique representation of the project as a whole, one which several users can remotely access in order to obtain information according to their individual needs. Any change in any component can be reflected throughout the project, including the effects on project schedule, and also likely implications on the structural loading and response.

In addition to the Structure Design for Fabrication process on the **3D**EXPERIENCE platform, Dassault Systèmes also provides solutions using Abaqus® simulation software for complex simulations and analyses, including for pre-stressed and reinforced concrete, for simulating the altered behavior of damaged structures, for geomechanics analyses for tunnels and foundations, and for seismic response analyses of complex structures. In the following sections, we present a few examples that show the use of Structure Design for Fabrication and Abaqus simulation software for simulating bridges and buildings.

SIMULATION FOR BRIDGES

Starting with a Dassault Systèmes' CATIA® model, one can use physics apps on the **3D**EXPERIENCE platform to create simulation models and perform analyses for events such as the movement of trains on bridge decks. One such example is shown below in Figure 2. Two balanced cantilever spans of a representative box-girder bridge are meshed, and finite element analysis is performed. A standard TGV train is considered to pass over the spans, and appropriate axle loads are taken into account at the wheel locations. The wheels are considered to be point masses, and vertical loads are generated at the point mass locations due to the action of gravity. Contact conditions are specified between the point masses and the bridge deck, and the set of point masses is then translated longitudinally over the bridge deck in order to simulate the passing of the train.

Figure 2 shows the contours of the component of tensile stress along the bridge's longitudinal direction as generated by the train's live load. One can see high tensile stresses along the deck top surface in the neighborhood of the pier as the train's weight is borne by the cantilever portion of the bridge deck. Although just elastic properties have been used for the bridge deck in this analysis, other material models appropriate for concrete will need to be used along with reinforcements and pre-stressing cables to get more realistic results. The latter will be essential when responses of the bridge to scenarios such as seismic and extreme loading need to be predicted.

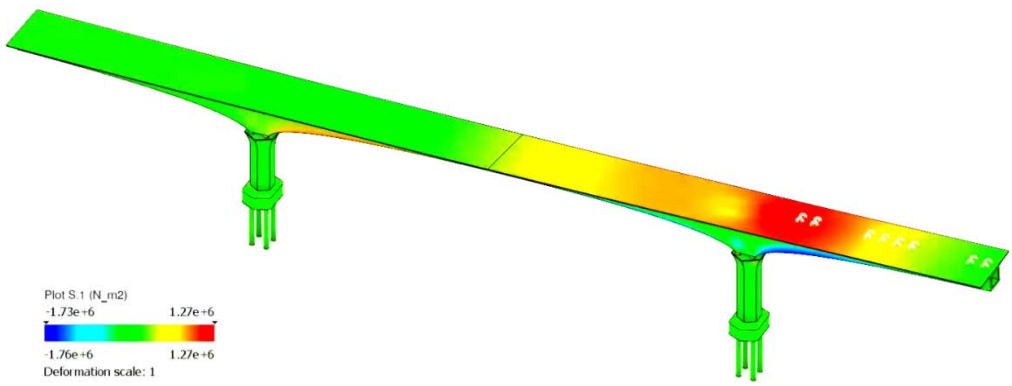

Figure 2.
Bridge showing contours of tensile stress along the axis. The tensile stress gets generated due to live load from the train.

Figure 3 shows a picture of the 8-lane, 1,907 feet long steel truss arch bridge over the Mississippi River on I-35 in Minneapolis, Minnesota USA that collapsed on August 1, 2007. National Transportation Safety Board and other agencies thoroughly investigated this collapse, and detailed finite element analyses were performed [Ref. 1].

Figure 3.
Picture of the truss-arch bridge over the Mississippi river that collapsed in 2007. Image courtesy: National Transportation Safety Board [Ref. 1].

Figure 4 shows a close-up view of a section of the bridge where the collapse initiated. Detailed analysis of the gusset plates and the connections was performed using Abaqus simulation software. The analysis led to the conclusion that the collapse occurred due to the gusset plate having insufficient thickness to bear increased loads. The increased loads were due to modifications to the bridge in combination with enhanced concentrated loads due to construction activities on the bridge on the day of the collapse. The contours in the picture show Von Mises stress values.

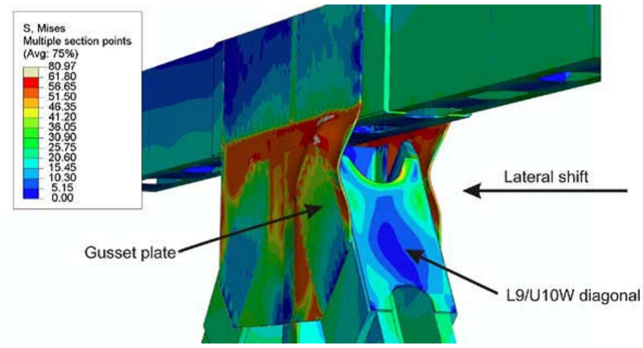

Figure 4.
A close-up view of the bridge section where collapse initiated. Contours show Von Mises stress values. Image courtesy: National Transportation Safety Board [Ref. 1].

SIMULATION FOR BUILDINGS

The **3D**EXPERIENCE platform provides a seamless way to model and analyze buildings using the CATIA Building Structure app. In this example, we model a 25-story steel building as shown in Figure 5. Representative steel members are used for the columns and beams. One scenario that is being investigated is the effect of loss of support at a set of columns in the center of the building.

Figure 5 shows the contour plot of vertical displacement due to the action of gravity. The effect of loss of support in the center is seen in the enhanced displacements in that region. Only the dead load of the structure is considered for this analysis.

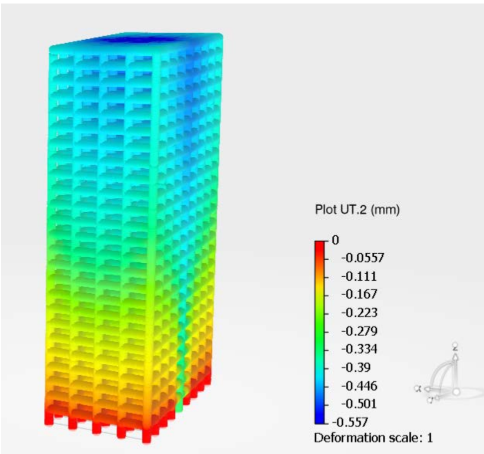

Figure 5.
Contours of vertical displacement of the building structure due to dead load. Enhanced displacements are seen in the central region.

Figure 6 shows contours of bending moment in the members due to the loss of support in the center. It is evident that the loss of support results in enhanced bending moments in the lower central sections of the building.

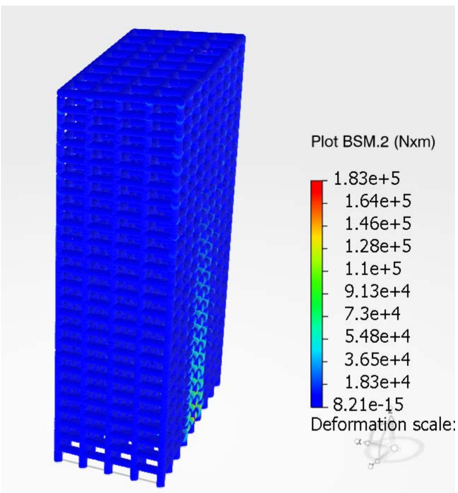

Figure 6.
Contours of bending moment in the members. Increased bending moments are seen in the lower central region of the building.

The example below shows the use of Abaqus simulation software for performing dynamic time history analyses of buildings that take into account material yielding and damage [Ref. 2]. An analysis on a trial design for the Dalian Xiaoping Island apartment building was undertaken, and the results from initial investigations on the plastic strain in a particular floor where the shear wall properties change are shown in Fig. 7. In this figure, the contours show maximum principal plastic strain values.

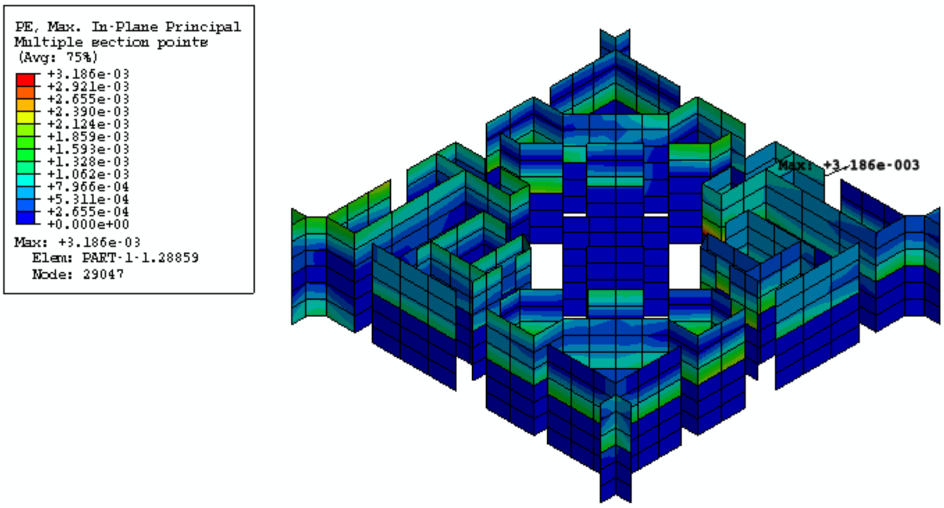

Figure 7.
Maximum principal plastic strain contours in a floor where the shear wall properties change [Ref. 2].

Figure 8 shows one of the Sun Valley structures constructed for Shanghai Expo 2010. These structures are single layer steel lattice formations made up of hollow steel tubes with rectangular cross-sections with members having solid cross-sections at the top ring. The stability of these structures had to be ascertained by performing detailed analyses.

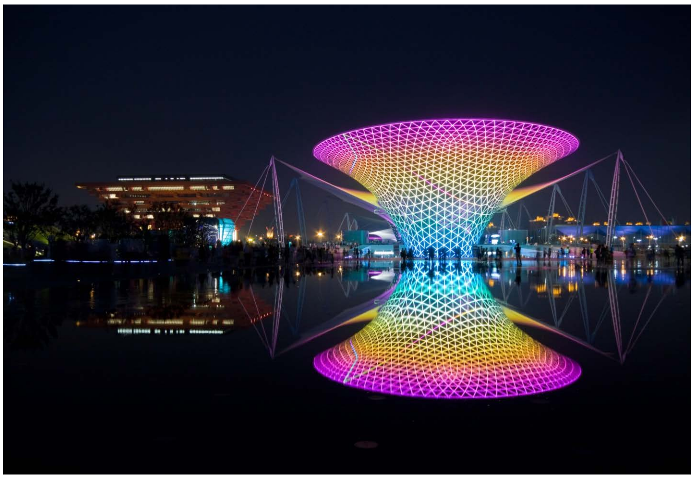

Figure 8.
One of the Sun Valley structures at Shanghai Expo 2010. Image courtesy: Shanghai Xian Dai Architectural Design Group.

Figure 9 shows contours of plastic strain for a representative loading condition for one of the Sun Valley structures. The advantages of Abaqus simulation software for these types of analyses include its capability to be a nonlinear solver that incorporates geometric and material nonlinearity, along with inclusion of material damage accumulation.

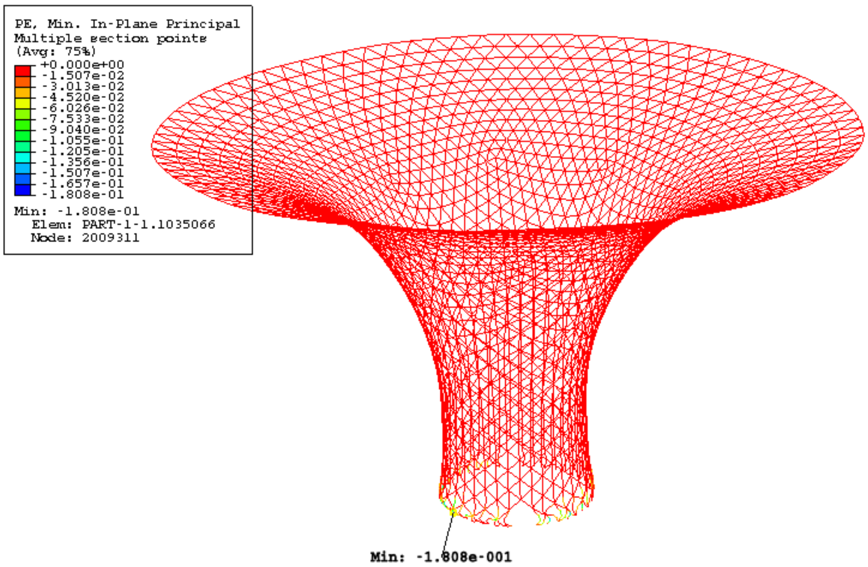

Figure 9.
Contours of plastic strain for a representative loading condition for one of the Sun Valley structures. Image courtesy: Shanghai Xian Dai Architectural Design Group.

Shanghai Xian Dai Architectural Design Group (SXDA) has been using the solutions provided by Dassault Systèmes for designing innovative structures [Ref. 3]. The solutions have enabled SXDA to achieve quality and excellence in their projects, along with minimizing costs. SXDA has designed several innovative structures including Shanghai's World Financial Center, the CCTV building in Beijing, the Zendai Himalayan Art Center and the Taihu Pearl Hotel.

The Zendai Himalayan Art Center's shape is bionic, with curved surfaces. The curved geometrical shapes were represented by SXDA using CATIA software, and the structural integrity was simulated using Abaqus simulation software, from Dassault Systèmes' SIMULIA® brand. Abaqus simulation software helped SXDA locate regions where additional reinforcements were needed and where reinforcement could be reduced. Using these types of optimization studies, SXDA was able to achieve 10 percent savings in the steel requirement for the structure. For skyscrapers such as the CCTV building, shown in Figure 10, and the World Financial Center, SXDA used Abaqus simulation software for performing simulations taking into account geometric and material nonlinearity, material damage, and the effects of material damage on the structural response due to seismic excitations.

Figure 10.
The CCTV building in Beijing. Image courtesy: Shanghai Xian Dai Architectural Design Group.

CONCLUSION:

Modern architectural designs involve innovative shapes and new materials. The structural behavior of such structures needs to be predicted accurately in order to achieve and maintain structural safety, reliability and utility.

The **3D**EXPERIENCE platform provides a seamless way to model and analyze buildings and bridges. Models can be created, meshed, and analyzed using connected tools available in the setup. For more complex cases, the available Abaqus simulation software capability can be used to perform sophisticated analyses, such as nonlinear elasto-plastic analysis including damage, coupled pore-fluid flow computations for foundations and tunnels, multiphysics studies including thermal and diffusional effects, and transient dynamic seismic analysis.

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