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Redefining glass through the design of innovative, full-glass structures

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DOI
10.1201/9781315229126-71
Publication date
2019
Document Version
Accepted author manuscript
Published in
Structure and architecture: Bridging the gap and crossing borders

Education on Structural Glass Design: Redefining glass through the design of innovative, full-glass structures.

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1 INTRODUCTION

ABSTRACT: In many famous architectural works, it is the structure and materiality of the building that manifest the project's innovation. In such works, the structural system of the building becomes the primary form of expression. Ergo, the ability to understand the principles of structural engineering and design, and the motivation to experiment with new types of structures and materials are invaluable assets for both architects and structural engineers. Towards this goal, a series of elective courses (Shell structures, Glass structures, Bridge Design) have been integrated in the curriculum of the MSc of Building Technology at the Faculty of Architecture and the Built Environment (BK) and of the MSc of Building Engineering at the Faculty of Civil Engineering and Geosciences (CiTG) at TU Delft. Aim is to bridge the gap between architects and structural engineers. Each of these courses lasts 10 weeks and focuses on the design, engineering, calculation and materialization of a different type of structure. This paper will discuss the set-up, learning objectives, methodology and output of the "*Technoledge-Glass Structures*"(BK) and the "Structural Glass" (CiTG) courses. Aim of these parallel courses is to effectively teach students, of both architectural and civil engineering backgrounds, how to design, engineer and evaluate the behaviour of structures made entirely out of glass elements and how to tackle problems related to the practical aspects of a construction.

Combining transparency with a high compressive strength, glass enables us to make diaphanous load-bearing compressive members, from beams and columns to free-standing facades and entire glass structures. Yet, structural glass design is a rather recent field of engineering. Although glass was first applied with a structural role in greenhouses more than a century ago, it is only in the last decades that its true structural potential has started to unveil. Indeed, recent developments in the fields of glass manufacturing and processing technologies have transformed glass from a fragile, brittle material to a structural component of high compressive load-carrying capacity. From the frameless suspended glass facades of the greenhouses in Cite des Sciences et de l' Industrie three decades ago (Rice,Dutton 1997) to the almost dematerialized glass structures by EOC Engineers (Eckersley O' Callaghan), glass's structural boundaries have been continuously stretching in the quest of maximum transparency (Albus,Robanus 2015). Yet, structural engineers and architects, alike, are still reluctant in using glass for structural components. After all, every person has broken a glass of wine or a window pane accidentally, but how many have broken a cup out of concrete? Few, if any. Concrete is also brittle and is actually less strong than glass, but people do not directly associate it with breakage. Aim of the Technoledge Glass Structures and Structural Glass courses is to alter the way architects and civil engineers perceive glass, by introducing them to the material's structural potential and effectively teaching them how to design and engineer glass structures.

2 COURSE DESCRIPTION AND CONTENT

2.1 *Course set-up*

The course on Structural Glass, first introduced in the academic year 2013-14, is given as an elective course (Technoledge Structural Design) for the students of the MSc Building Technology at the Faculty of Architecture. The course is given twice per year, accounts for 3 ECTS and lasts one academic quarter. In the faculty of Civil Engineering the course (Structural Glass), previously an elective, has become compulsory for the students of the MSc Building Engineering since the academic year 2018-19 and accounts for 4 ECTS. All students work on the architectural design and its validation, yet architecture students emphasize more on design aspects while civil engineering students on structural calculations. The principal learning objective of the course is to familiarize students with glass as a structural material.

In both faculties, the course lasts one academic quarter of 10 weeks and is evolved around the design, detailing and structural calculation of a full-glass structure. The average number of students participating in the course is approx. 20-25 during the spring semester and approx. 10 during the fall semester. The normal scheduling of the course comprises two hourly lectures and two hourly design studio sessions per week. The students are also asked to give three presentations: one on the 2nd week on their initial design idea, a mid-term presentation on the 4th week and a final presentation on the 8th week. After the final presentation, the students have two more weeks to work on their final report on their glass structure prior to submitting it. The final assessment of the students' work is based on their design progress, final presentation and report. Table 1 gives an overview of the set-up of the course.

Table 1. Structural Glass course set-up

Week number	1	2	3	4	5	6	7	8	9	10
Lectures	x	x	x	x	x	x	x			
Studio Sessions	x	x	x	x	x	x	x			
Presentations		x		x				x		
Assignment (Design)		x	x	x	x	x	x	x	x	x

2.2 *Learning objectives of the course*

The principal learning objective of the course is to familiarize students with glass as a structural material. Through the architectural and structural design of an all-glass structure, the students get to know the mechanical properties of glass, its boundaries and safety concerns, and how to apply it as a safe structural material on innovative architectural applications. In specific, after completing this course the students are expected to be able to:

- explain the basic mechanical properties of glass and argue on its proper structural application.
- design full-glass structures with minimal use of opaque connections.
- explain and apply the size limitations of float, cast and extruded glass components due to their fabrication and transportation processes and cost.
- explain the advantages and disadvantages of the basic types of glass connections and implement safe connections between structural glass elements.
- identify and describe the main risks involved in a glass structure and to implement safety measures.
- calculate glass structures with the aid of hand calculations and FEM programs, and evaluate the data.

3 METHODOLOGY

Both courses evolve around the design of a full-glass pavilion or a small glass tower. The design process lasts 10 weeks and stretches from the development of an architectural concept, to the dimensioning of the elements, detailing and structural verification. In this way, the students apply in their own design project the fundamentals of glass engineering, which are introduced to them through the lectures. This calls for the students to come with customized solutions for their individual design, perishing as well the risk of having students ending up with identical solutions. In specific, the scheduling of the *Structural Glass* sub-studio in Architecture and the *Structural Glass* course in Civil consist of two lectures of one hour each and one design studio session of two hours per week. The lectures are common for the architecture and civil engineering students, however the studios are customized to the different background of the students. Lectures given every week provide insight and the required theoretical tools for the students to work on their final assignment. Depending on availability, guest lecturers from engineering companies are also incorporated into the regular lectures. The lectures cover aspects of structural mechanics related to the assignment, present an overview of relative realized structures as well as examples showing the potentials and risks of the use of such an innovative material in construction. The students employ the above theoretical concepts in their practical assignment. Working in teams of two to three (the students are free to choose their team members), they are asked to develop, detail and engineer their own design for a full-glass structure and evaluate it by means of structural calculations. The development of the design is guided during the weekly workshop sessions by one-to-one consultations with the instructors. The weekly studio sessions give the students the opportunity to discuss all their questions with both the tutors and their peers. In addition, by giving two mid-term presentations the students are able to receive formative feedback from all tutors as well as from their peers on their work, essential for improving their project and thus their assessment performance. The studio sessions are organized in such a way so as to tackle the following aspects of the glass design solution of each student team:

1. Architectural design

The form of the structure is up to the students' design, as long as it fulfils the general requirements and space specifications. The students initially think on how to shape the structure and speculate on the size and thickness of the main glass components based on existing glass structures. They are encouraged to escape the two-dimensional image often linked to structural glass applications and develop innovative and challenging designs that push further the limits of the current state technology. By introducing them to the state-of-the-art glass production and post-processing techniques, the vast possibilities on hand are unveiled. Students achieve complex shapes with float glass, by employing waterjet cutting, bending and/or corrugating techniques. Moreover, advances in the application of extruded and cast glass achieved by the TU Delft Glass and Transparency Research Group are directly fed to the education stream.

2. Build-up of components

Several factors, such as the fabrication limits of glass, the autoclave dimensions, the size of the transportation containers and the assembly process restrict the size of individual glass components. By taking all these aspects into account students are called to define the structural grid and dimension the glass components (fig.1).

3. Detailing

The students have to design the connections among the main structural glass elements. The goal is that the connections result in minimum visual impact in order to allow for maximum transparency while ensuring the desired strength and mechanical performance. The students are also called to take into account and present the building sequence of the pavilion (fig.1), so as to create accessible connections when assembling the structure.

4. Safety Analysis

Students have to make a risk and consequence analysis concerning damage or even total collapse of their structure and propose measures to ensure the safety of the construction.

5. Structural verification

Structural verification is done mainly by hand calculations in order to investigate deformation and stresses on individual elements, as well as on the structure as a whole. Where the complexity of the design requires it, the calculations are further performed with the support of FEM software (fig.2). Students may as well parametrically design their structure using *Rhino's* plug-in Grasshopper, and employ *Karamba* plug-in for their calculations. The civil engineering students also use *SJ Mepla* for calculating planar components in their design.

6. Final design

To optimize the shape and structure, the final design incorporates the findings from all the above addressed aspects. For example, the structural calculations that can lead to changes in the structural grid and the dimensioning of the structural elements.

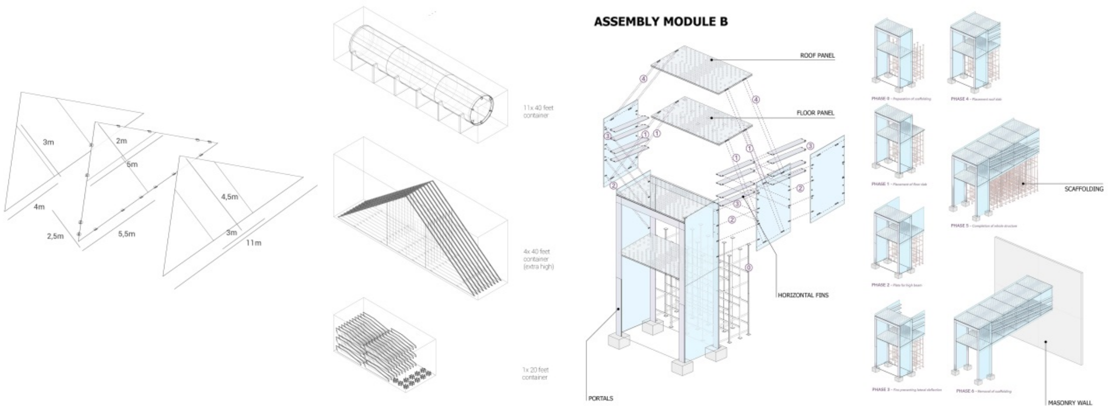

Fig.1: Left: Design considerations based on the limits of the glass manufacturing and processing lines. Work by students J. van Veen, N. van der Knaap Right: Assembly sequence of the structure by students D. Vitalis, V. Plaza Gonzalez.

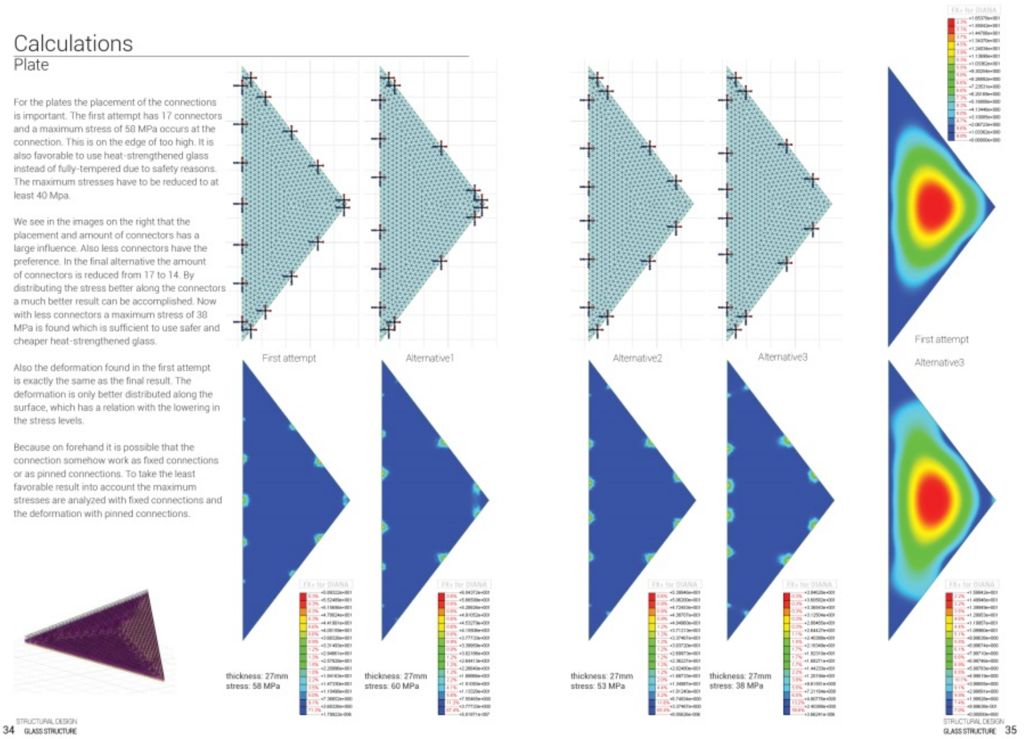

Fig. 2: Structural calculations performed in Diana software by students J. van Veen, N. van der Knaap

To ensure the alignment between learning objectives, teaching activities and assessment criteria the studio sessions correspond each to a learning objective with the assessment criteria formed to match what is taught in class.

Table 2. Alignment between learning objectives, teaching activities and assessment criteria

Learning objective	Teaching activities and assessment form of the learning objective	Assessment criteria
explain the basic mechanical properties of glass and argue on its proper structural application	Frontal lectures (in the future by flipped classroom method). Ask and answer questions and discussions during studio sessions. Assessment through a written reflection on the student's design at their final report and presentation.	Reflection on how the design evolved based on a summary of the mechanical properties of glass
design full-glass structures with minimal use of opaque connections	Lectures analysing case-studies. The students have to implement the presented design principles in their design assignment of an all glass structure.	Architectural design of the glass structure with provided description and analysis of the concept
explain and apply the size limitations of float, cast and extruded glass components due to their fabrication and transportation processes and cost.	Information transfer through lectures. In their design assignment, students have to apply the actual size limitations in glass to dimension their components.	Application of the limitations due to manufacturing & logistics in the sizing of the glass components. Assembly order of the structure.
explain the advantages and disadvantages of the three basic types of glass connections and implement safe connections between structural glass elements.	Lectures, peer instruction. The students then have to develop connections for their glass design and elaborate on their choice.	Analysis, design and assembly of the main connections between structural elements.
identify and describe the main risks involved in a glass structure and to implement safety measures.	Lectures. During the studio sessions students are asked to think of what-if scenarios in specific case studies and propose safety measures to reduce risk. They have to apply the same principles in their design.	Risk analysis & application of safety measures on the design
calculate glass structures with the aid of hand calculations and FEM programs, and evaluate the data.	Lectures, lab work, structural analysis on the students design.	Structural analysis of the glass structure and redimensioning based on the results

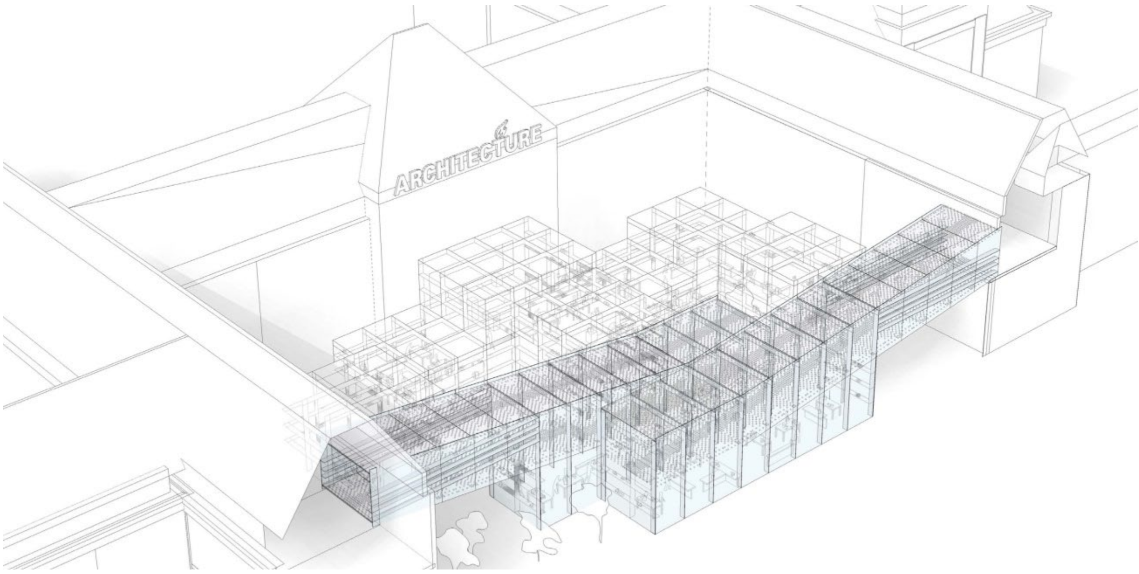

Fig.3: Final design by students: D. Vitalis, V. Plaza Gonzalez

4 RESULTS

Figures 3-5 demonstrate some results from the students since spring 2015. Several different design assignments have been given, from a 30x12m glass pavilion, to a glass extension of the Faculty of Architecture of TU Delft, to a full-glass observatory for the Aurora Borealis in Iceland.

Fig.4: Final designs from the spring 2018 course with assignment the design of an all-glass observatory for the Aurora Borealis in Iceland(Students: N. Christidi, R. Estrado, Y. Sakthivel, B. Yong, S. Kamble, F. Zielinski, F. van der Weijst, R. Groenendijk, A. Boonstra, W. Damen, S. Brugman).

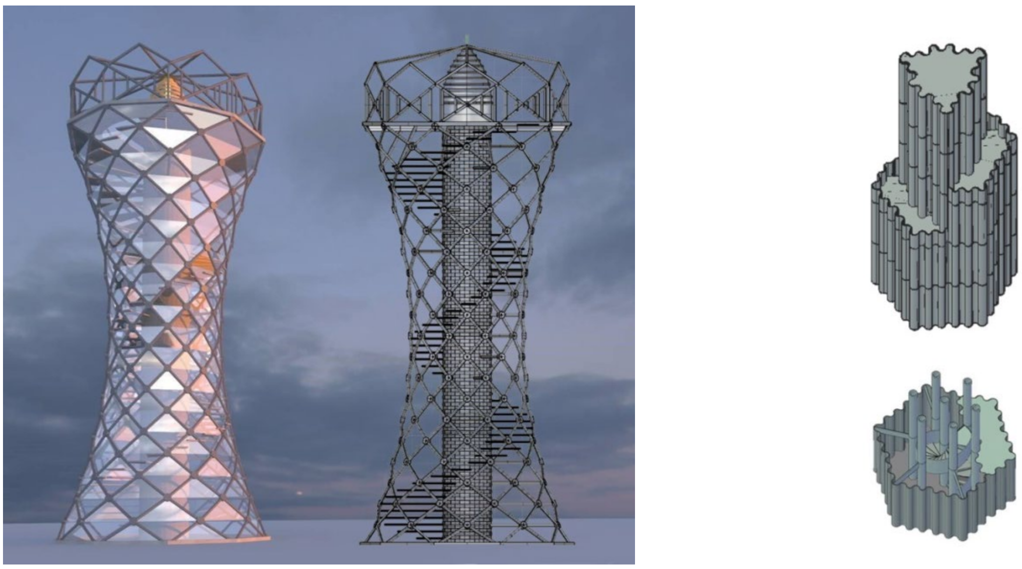

Fig.5: Left: Glass Lighthouse employing glass rod bracings and a cast glass brick core, by P. Peeters and J. Salitrežić. Right: Glass Lighthouse out of a structural corrugated glass façade, hollow tubular columns and waterjet cut float floors, by B. Pompei and R. Nijman.

5 COURSE SPECIAL EDITIONS: BUILDING WITH GLASS.

A special edition of the Structural Glass course in Architecture has been given twice (fall semester 2016 and 2017), where all students have worked in one team in order to design a glass structure and then build a scaled prototype of it. The students had to follow the same course set-up but put more emphasis on parametrically improving their structure and use 3D printing for the fabrication of the connectors between the glass elements. The last two weeks of the course were reserved for the prototype making.

5.1 *Fall semester 2016 course: An organic glass structure*

In Fall 2016 a team of seven students designed and built part of a glass pavilion in 1:3 scale where the loadbearing elements were optimized parametrically based on their structural performance (fig.6). This resulted in organic-shaped glass elements with cavities where there were low stresses. To achieve the desired shapes, the elements had to be waterjet-cut by a specialized company. Due to time restrictions, instead of lamination the students used a double-sided transparent tape to bond the multiple panes together. Special, custom-made 3d printed Polylactic acid (PLA) connectors were fabricated at TU Delft to connect the columns and roof plates.

Fig.6: Final prototype of the structure in 1:3 scale.

5.2 *Fall semester 2017 course: A full-glass sandwich floor*

Based on prior research at TU Delft by (Vitalis et al. 2018), an all-glass sandwich floor was designed, developed and built in 1:2 scale by a team of seven students (fig.7). The goal was to create a structural glass element with high stiffness to weight ratio: a sandwich glass panel where the core elements are also made of glass. Special attention was given to the resulting pattern of the spacers. The students decided to create a core-free area in the middle of the floor, so that an object can be exhibited below. Thus, core elements surround the central core-free area and through a gradient design are distributed to the rest of the panel, densifying at the outline of the floor where stresses are expected to be the highest. The final design of the core distribution was done parametrically in Grasshopper. Different glass elements were considered for the core elements. Eventually, the students opted for extruded star-shaped glass rod profiles made by SCHOTT. Special, custom-made 3d printed connectors, following the shape of the star profiles were made by the student team to enable the connection of the two panels without compromising the overall visual result. The resulting visual prototype demonstrated the great potential of glass sandwich panels as a relatively lightweight, transparent yet stiff structural component. The research on design and fabrication conducted on this course set the basis for the manufacturing of three 1.5x6 m glass sandwich panels that were exhibited at GlassTec 2018 fair in Dusseldorf.

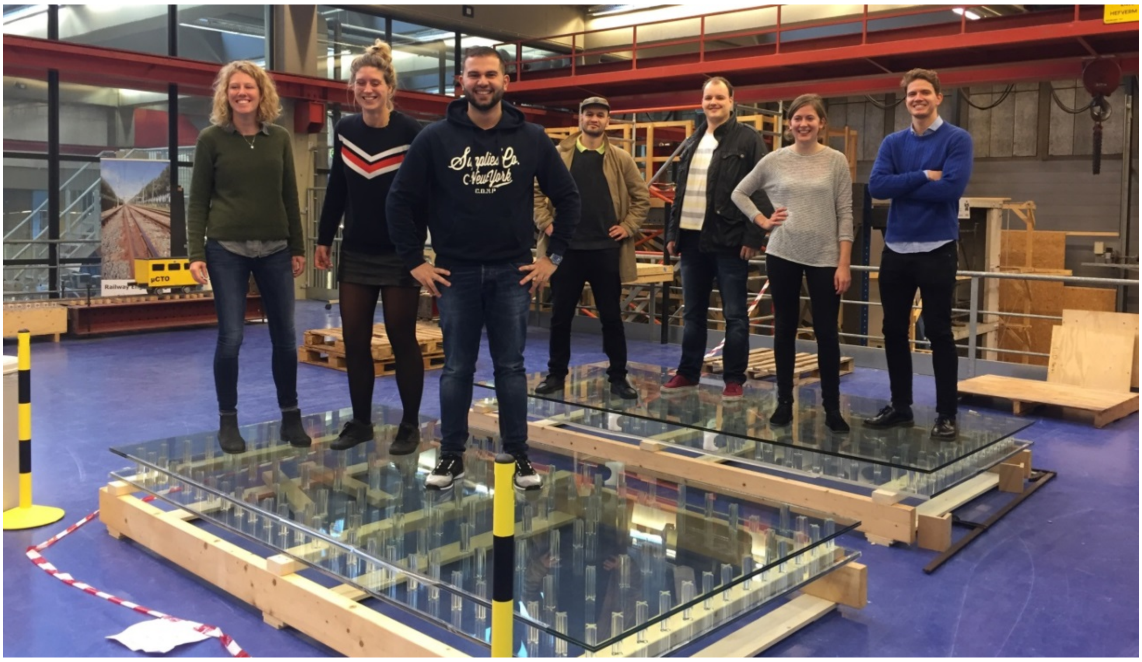

Fig.7: The 1:2 scale prototype made in Technoledge Structural Design Course 2017. Student team: Liesanne Wieleman, MJ Veenendaal, Joep Nizet, Bram Rooijakkers, Charbel Saleh, Franke de Haan, Anne Bruggen

6 CONCLUSIONS

Through the Technoledge Structural Glass course at the Faculty of Architecture and the Built Environment, and the Structural Glass course at Civil Engineering and Geosciences, TU Delft MSc students successfully learn to trust glass as a structural material. During the structural design phase, glass is from now on included in their list of suitable materials. Furthermore, glass is not only conceived as a flat entity, but rather as a material able to take any form envisioned. Yet, designing a safe glass structure is of crucial importance. By identifying the strong and weak points of the material, and the risks involved during production, transportation and installation, the students are able to properly engineer their designs. The incentive for innovation and challenge results in a variety of fresh ideas and designs that advance the field of structural design.

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