# Architectural Design and Structural Analysis for Steel–Glass Structures

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Contributor: Faham Tahmasebinia , Shaoxiong Jiang , Sara Shirowzhan , Lewis Mann , Samad M. E. Sepasgozar

It is well known that finite element analysis (FEA) is a powerful tool when it comes to the design and analysis of complex structures for various load combinations, including light steel curve members. FEA simulations can provide valuable insights into the behaviour of light steel curved members under different load combinations. This enables designers to optimise designs for strength, safety, and cost-effectiveness. Using two commercial 3D software programs, Rhino 7 and Strand7, to complete the FEA simulation of light steel curved members.

steel-glass structures | curved steel members | global structural performance | Finite Element Method | Buckling Analysis

## 1. Steel–Glass Structure

Steel and glass have become increasingly prevalent in architecture due to advancements in design concepts and construction technology. In recent decades, there has been a growing body of research on steel–glass structures, resulting in a significant increase in literature on the topic. With improved material properties, steel and glass have demonstrated excellent mechanical performance, surpassing previous expectations regarding their resistance to buckling and breaking. Steel and glass are often combined for their aesthetic and structural value, particularly in steel–glass façades. In this type of construction, the structural frame is typically made of either steel or aluminium, with glass panels serving as the cladding material [1]. The steel frame is erected first, forming the required shape, and then the glass panels are carefully fitted and connected to the frame using a specific process. The resulting steel–glass structure can replace concrete walls and roofs, offering cost reduction, improved indoor illumination, and enhanced aesthetic appeal.

## 2. Advantageous of Steel–Glass Structures

### 2.1. Cost

Despite its ability to improve indoor illumination and create a distinctive spatial experience, the steel–glass grid shell structure is expensive. Unfortunately, no comprehensive cost comparison has been conducted between brick, timber, concrete, steel, and steel–glass buildings. The practice experience in the industry and relevant feasibility studies are valuable sources of information.

Compared with traditional structures, steel–glass structures are potentially more expensive, but require little maintenance. The glass panels can be cleaned easily, and the steel beams can be prevented from corroding by painting and coating. Further, a complex curved steel–glass façade can be used where both straight and curved steel members can be used. Admittedly, straight members have relatively low prices compared to curved steel structures and are easier to manufacture. The additional cost caused by the curved steel members is minimal compared to the cost of the entire steelwork. Moreover, the extra expenditure can be offset by reduced ridge detail and flashing costs for structure spans less than 25 m [2]. Additionally, the cost of the steel–glass construction can be further minimised by utilising advanced form-finding and structure analysis techniques.

## 2.2. Sustainability

By improving indoor illumination and regulating temperature, steel–glass structures can contribute to energy efficiency. Undoubtedly, the steel–glass structure can improve the quality of indoor lighting. Glass is a material with high transmittance and transparency that allows sunlight access. While the steel structure is the main supporting part, its size is smaller than the glass part. Since traditional buildings are mostly brick, timber, and concrete structures, sunlight can only be accessed through windows and skylights. A glass panel with insulation capacity may also be incorporated into the design, facilitating the control of the building’s heating and cooling.

## 2.3. Atheistic Value

Steel–glass structures can improve the aesthetics of a building. Architects can convey their design concepts with another level of flexibility through structural design. Thus, irregular-shaped structures need to be considered in structural design processes. For irregular-shaped steel–glass structural design, curved members are often used instead of straight members. They are more reliable due to the efficiency of arches and other vertically curved structures [3]. Moreover, in some scenarios, the straight steel members may not be appropriate, and only curved structural members can be used. Moreover, steel–glass structures can provide flexibility in the architectural design process. As a result, it can create a larger open space and satisfy the specific needs of the design.

Steel–glass structures are considered attractive in Japanese architecture. This type of architecture symbolises modernism and vernacular concepts from an aesthetic standpoint. Furthermore, the choice of structural composition significantly impacts the realistic outcomes of the steel–glass structure. Kido et al. [4] provide several examples of typical Japanese practices. Several architectural methods are presented, including those that pertain to railway stations [5], passenger service centres on expressways [6], air terminals [7], and commercial and public buildings [8]. Steel–glass structures were designed to comply with both classical aesthetic values and local cultural traditions. Therefore, the systems can be considered novel art. They [9] also discuss the evaluation criteria of the steel–glass compartment in the building. Dimensions, visual lightness, texture, reflection, transparency, colour, light, translucency, and the design context are all considered. This creates a special visual experience for visitors.

Helbig and Oppe [10] present the roofs and façade design of the United States Institute of Peace, Washington, D.C., and explain the symbolisation of the free-form steel–glass grid shell.

Therefore, the atheistic value of steel–glass structural design is widely acknowledged in the architectural industry. As a result, it can add a layer of cultural and artistic significance to the building.

### 2.4. Mechanical Performance

With the development of the engineering material manufacturing industry, both materials can have satisfactory mechanical properties, especially glass. Different types of glass panels have been discussed regarding their mechanical performance and design principles [11]. Based on extensive research into the strength and durability of glass material, the safety of its use can be assured [12]. Steel is an unquestionably strong material that is resistant to buckling and breaking. It has a remarkable load-bearing capacity.

### 2.5. Parametric Modelling Method on Irregular Steel–Glass Structures Design

As a result of the development of building information modelling techniques and the development of the relevant modelling software industry, irregular-shaped steel–glass structures can be designed and optimised efficiently. Modifying and iterating the parametric model may be convenient. By employing parametric design, it is possible to increase the efficiency of work since irregular models must be adapted multiple times to meet technical requirements and client requirements. A number of add-ons are available for the parametric design software, which enable the design of irregular structures, as well as form-finding and mechanical simulation functions. Algorithms can be used to analyse structural and energy efficiency, as well as cost-effectiveness. Parametric design can also improve the accuracy of modelling and provide parametric data that can be used to assist in the construction and manufacture of structural members. By enabling easy sharing and modification of the models, collaboration among different specialties can also be facilitated. Parametric design software is widely available in the industry, including Grasshopper (visual programming editor for Rhino) and Dynamo (plug-in for Revit). Design requirements and designers’ requirements are considered when selecting software.

## 3. Active Research on Steel–Glass Structures

### 3.1. Materials and Steel–Glass Composition

Building envelopes are usually constructed of glass or metal. Innovative building skin systems can contribute to the evolution of modern architecture [13]. Segura and Feldmann [14] propose that the glass elements are subjected to a combination of wind loads and static loads transferred from the entire structure. This can lead to uncertainty in structural analysis. In this study, the dynamic effects of laminated glass panels as a load-bearing element are examined using basic modal identification techniques. Netusil and Eliasova [15] investigate a composite steel–glass structure, and the ultimate load of such a hybrid structure is predicted. The study presented by Grenier et al. [16] provides guidelines for the design of hybrid steel–glass beams and steel–glass façade systems. In addition to steel flanges, the beams are composed of a glass web. The steel and glass members adhere together to achieve the required structural performance. Rao et al. [17] examine the potential effects of nanotechnology on civil engineering materials, including steel and glass, and their properties, including improved durability, strength, and energy efficiency. According to Netusil and Eliasova [18], adhesively bonded steel–glass composite I-section beams, as well as the possible factors that may affect their performance, have been statically evaluated. According to Pravdova et al. [19], the initial imperfections in hybrid steel–glass beams can contribute to their instability.

## 3.2. Steel–Glass Connection

A steel–glass composite system can be assembled using adhesive junctions. The overall performance can satisfy the technical, aesthetical, and energetic requirements [13]. Kruijs et al. [20] describe the design of a glass bearing connection that is associated with an acceptable level of stress, as defined by Eurocode EN1990 CC2. A study by Nhamoinesu and Overend [21] examines the mechanical performance of adhesives used in a steel–glass composite façade. The adhesive joints are simulated, and the stress states are determined by an analytical and a viscoelastic-plastic numerical model. A series of recommendations can be made based on the results for the selection and application of adhesives for steel–glass composite façade systems. Using finite element analysis (FEA), Richter et al. [22] investigate the stress state of adhesives in multi-side bonding under varying loading conditions. According to the experimental results, as glass thickness increases, a decrease in the impact of the non-linear adhesive characteristics on the total structural behaviour of the glass can be observed. A series of experiments were also conducted by them [23] concerning multi-sided bonded joints on steel–glass façades. Steel frames with L and U shapes support the glass panels between 6 and 15 mm thick. During this test, two types of adhesives were used, 2C silicone (SI) and 1C polyurethane (PU). As a result of this experiment, essential information about safe design procedures for such bonded joints is provided. A multi-span bridge welding technique is proposed by Musalev et al. [24], along with the welding parameters for steel–glass liners. According to Tutunchi et al. [25], the addition of Al2O3 nanoparticles to a two-part structural acrylic adhesive can enhance the bond strength and durability between steel and glass. As part of their study [26], silica nanoparticles were also added. An investigation by Van Lancker et al. [27] examined the strength behaviour of adhesive bonds under extreme environmental conditions. The study by Odenbreit and Dias [28] shows that adhesive jointing can increase the load-bearing capacity of steel–glass beams. Ligaj et al. [29] investigate the value of stresses in glued aluminium alloy and glass joints in vehicles under conditions of four-point bending. During the testing process, the stress is related to damage that is initiated in the joint being tested. In a study by Chavooshian et al. [30], silicon carbide nanoparticles were added to steel–glass/epoxy composite joints bonded with two-part structural acrylic adhesives in order to enhance adhesive strength. An investigation of steel–glass orthogonal lap joints with silicone adhesive was undertaken by Wang et al. [31]. According to the study, failure is related to the thickness of the adhesive and the overlapping length of the composition. Using this analytical formula, the shear strength of the bond is then determined based on the equilibrium of strain and force. In Amstutz et al. [32], digital image correlation is used to measure a polyurethane adhesive’s local multiaxial deformation behaviour. These outcomes can be used to identify a constitutive material parameter and to formulate hyperelastic materials models. In this way, the non-linear elastic behaviour under multi-axial loading conditions can be predicted using finite element analysis. A study by Katsivalis et al. [33] investigated the stress states and failure behaviour of adhesives used in the connection between mild steel and tempered glass. The researchers conducted a numerical simulation in order to determine the adhesive pressure-sensitivity, plasticity, and failure mechanisms, as well as to determine how the adhesive will behave overall over time. A study by Biolzi et al. [34] examines the behaviour of silicone-bonded joints for steel–

glass structures at high temperatures. Various structural adhesives are evaluated based on their mechanical properties.

## 3.3. Analysing Methods and Industry Standards

Architects are constantly striving to create transparent and delicate structural elements. In recent years, glass has become an increasingly popular alternative to concrete walls and roofs. The use of it in the façade is also an example of this. As a result, glass is gradually becoming a mainstream element of space enclosing, but it is also receiving greater attention for its capacity to bear loads. Special-shaped buildings with complex curved façades and roofs are often constructed with steel–glass structures. The shapes can be intuitively expressed as a part of the original design concepts from the architects. Thus, an analysis of the structural integrity of this building structure is required. In the industry, however, the relevant design standards need to be present. Moreover, due to the complexity of the curved surface shape, each case has an entirely different shape and structure. In terms of precedents, a few can be used as examples. Among other things, Adriaenssen et al. [35] describe a method used to determine the adhesive properties for non-linear numerical simulations of structural steel–glass connections and present the mechanical behaviour under different loading conditions. After proving the feasibility of the method, they offer a real-life case.

The study by Richter et al. [36] examines the nonlinear stress–strain behaviour of steel–glass façade panels with multi-side bonding under complex loading scenarios and provides guidelines for designing such boards. Dias et al. [37] describe the development of constitutive hyper-elastic material law and implementation of the law for numerical simulations using the finite element software Abaqus. Through this method, the structural silicone for steel–glass connections is simulated, and the results are in agreement with those obtained during the experiments. According to Espinha et al. [38], the geometry and structure of the terminal building at Baku Airport in Azerbaijan were designed during the design process. In addition, they describe the impact that construction and seismic considerations have on the design concept. In Pravdova and Eliasova [39], the lateral and torsional stability of the steel flanges and glass web connection is examined. Based on Wang et al. [40], laminated glass webs with steel flanges may have a higher ductility than glass panels. The authors conduct an experimental analysis of the behaviour of the hybrid beams under in-plane shear compression and assess the influence of adhesive on their behaviour. It is evident from the results that the test sample has higher strength, and the mechanism proposed gives a better prediction of strength than the formulas referred to. Hoffmeister et al. [13] demonstrate the possible application of glass panels having hyperbolic paraboloid shapes to steel–glass structures. In the late 1990s, Adriaenssens [41] described an approach to form-finding and structural analysis developed by Michael Barnes. Numerous architectural designs have been created using this technique, including the steel–glass dome of the Dutch Marine Museum. As an extension of Grasshopper in Rhinoceros, a program that provides parametric modelling, the concept is also utilised in Kangaroo, a mechanical analysis plug-in for Grasshopper. As a result of lateral torsional buckling of glass beams with lateral restraint, Adriaenssens [41] investigates its mechanisms. To complete the research, they resort to finite element simulations and apply the theory of buckling curves and non-dimensional slenderness factors. Moreover, Eliasova and Pravfova [42] studied the lateral torsional buckling of steel–glass beams. In this beam, glass webs are connected by steel flanges. A study conducted by Firmo et al. [43]

examined the composition details of an I-shaped hybrid steel–glass beam (HB) and the safety of the design. A comparative analysis is performed of four prototypes in order to examine the global deformation behaviour, as well as the distribution of strain and cracks. Using such a technique can aid in the development of relative design concepts and assembling strategies. The study by Tahmasebinia et al. [1] examines the load performance of a steel–glass spindle torus shape structure utilising Strand7 (R2.4.6) and ABAQUS (6.14), referring to the Jewel Changi Airport in Singapore as an example. On models with straight and curved steel members, there seems to be a divergence in the structural analysis results. Beam buckling behaviour can be affected by boundary conditions, L/R ratios, and boundary conditions. Using a tensegrity floor design, Scoccia et al. [44] examine the structural performance of this innovative concept. A specific steel–glass joint adhesive technique is used in this technique, which facilitates the combination of different materials. As a result of their investigation of the nodes and joints of steel–glass lightweight floors, Marchione et al. [45] constructed a prototype based on the tensegrity floor technique and investigated the application of adhesive. Verification of the structure's actual behaviour is conducted.

## 3.4. Industry Application of Steel–Glass Structures

A case study of the glass canopies at the Lincoln Center is presented by Knippers et al. [46], which discusses the structural and architectural features of the steel–glass structures. Several factors must be considered when designing the hybrid steel–glass building skins and their connections, as highlighted by Silvestru et al. [47]. Heimbig et al. [48] introduce the free-form steel-and-glass canopy covering the atrium of "Casas hopping," a luxury home furnishings centre in Rio de Janeiro, Brazil. Prefabrication of the high-precision node–beam system was used in this project, which posed a challenge to the construction team. Defalco et al. [49] propose the use of external hybrid steel–glass frameworks to consolidate reinforced concrete structures in social housing. The numerical calculations and design considerations of the insulated glazing units used in this project are presented by Heinze et al. [50]. Maier et al. [51] propose an extension project for the university's central refectory. A spannable entrance yard is achieved through the use of the steel–glass structure. By combining the design of the renovation of existing facilities, underground engineering, reinforced concrete structures, and other fundamental fields, the BIM technique is used in this project. One of the steel and glass structures that can be found at Kazakhstan Expo is the Sphere. This bridge was built to connect two adjacent buildings in Germany, which became the headquarters of one corporation. Mahl et al. [52] described this bridge as having a complex crystalline-like shape. It is known as Capricorn Bridge and is made up of polygonal elements of glazing. Building axes, circulation patterns, and existing building circumstances contribute to the complex shape of the glass surface. During the design of the new science building of the University of Basel, a skylight was designed to cover the central atrium. As a result of the grid shell structure, the atrium was able to achieve the required amount of indoor illumination. An approach called form-finding was used to model the shape [53]. According to Adriaenssens [54], Laurent Ney is well-versed in digital and numerical methods of shape-finding and optimisation, as well as providing construction guidelines as a structural designer. As an architect, he was involved in the design processes of the Dutch Maritime Museum and the Knokke Lichtenlijn footbridge. There were two types of steel–glass structures designed by him for the two cases, namely, a grid shell and a hanging steel shell.

## 3.5. The Application of Building Information Modelling (BIM)

A BIM system allows the application of prefabricated building modules in a missive manner [55]. The system is capable of realising the entire design concept. In addition, it can provide the capability to manage and evaluate a plurality of significant aspects of the building process. Design stages can be communicated more effectively, and designers' workload can be reduced as a result. As well as optimising structural efficiency or cost, it can also be utilised for other purposes. Based on algorithms, Nazar and Slyk [55] developed structural control modules and computational methods that are applicable to masonry, steel, glass, and timber structures. The authors argue that the systematic application of BIM and efficient project management methods contributes to the success of their study. A steel–glass system is being constructed using extended reality (XR), a visualisation technique, as part of the construction process. Furthermore, they explore the relevant wireless networking technologies and optimise the interaction between different software modules. Afterward, a discussion of how the industrial internet of things and augmented reality technologies will develop in the future is presented.

Over the past decade, it is evident that there has been an increased level of research activity in the steel–glass structure field. As a consequence of the literature mentioned earlier, valuable information can be gained regarding steel and glass materials and composition, steel–glass structure connections, advanced structural design and analysis techniques, and their application in various industries. In the present study, methods of parametric modelling and structural numerical analysis will be investigated in more detail for irregular-shaped steel–glass structures with straight and curved structural members with straight and curved constituents. Additionally, the entire working flow will be demonstrated from the modelling to the structural analysis phases.

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