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Numerical Simulation and Analysis of the mechanical behaviour of Cable supported Glass Façades

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First of all, I would like to express my gratitude towards the company Meinhardt Façade Technology (MFT) for bringing me the opportunity to get a first-hand exposure to the world of façade engineering services and consulting and a chance to start learning and understanding the inside of a multinational company. During the course of my 6-months internship at Meinhardt, I was able to gain valuable experience from all the staff who were always very welcoming and helpful, and I am specially thankful to my supervisor Lisa Hu, civil engineer and senior façade engineer, for kindly taking the time to share her expertise and knowledge with me and for guiding me through the realization of this thesis.

I would also like to thank Dr. Luca Pelà, PhD, for his advice and guidance as my academic tutor, being a fundamental figure in this thesis for his wide knowledge in construction engineering and numerical modelling and his broad experience in research theses.

Last, but not least, I acknowledge and dedicate this thesis to my beloved mother, for always being so supportive and encouraging, not only through the realization of this thesis but also throughout all the years of study in Civil Engineering.

Title: Numerical Simulation and Analysis of the mechanical behaviour of Cable supported Glass Façades

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In the last years, the desire to maximise the transparency of glass wall structures has pushed engineers and designers towards using high strength steel cables as supporting and stiffening members in glass walls. The cables, when arranged in a rectilinear grid and tensioned proportionally to their breaking strengths, create a structure significantly resistant.

With the introduction of pre-stressing and cable nets, modern building facades and walls can be designed to be large scale, light in weight and highly transparent. It is a simple system that offers the ability to span great distances without the need for large, heavy structured elements within the glazed area. Moreover, it provides advantages in terms of flexibility and simplicity in construction, together with a modern aesthetic sense that creates a perfectly integrated space between indoor and outdoor environments.

It is important to fully understand each component's performance and its associated influence on the other components in the system. The cable system behaviour under loads and deflections directly influences the design of the glass attachment and therefore the glass plates forming the cladding.

This thesis aims to contribute to the evolution of structural glass technologies by presenting an analysis of a façade prototype and intends to provide insight on the mechanical behaviour of these systems.

A numerical simulation of the prototype in its configuration combinations is modelled and a non-linear static analysis is run using the finite element method.

The main components of the system are individually approached and observations are made on the type of attachment used. Special attention is brought to the behaviour of the glass panels since it is the capabilities and loading of the glass that defines the basis of the design for any back-up structural system.

The feasibility of the presented prototype is assessed by analysing and comparing the results obtained for the different situations, and relevant conclusions and recommendations are drawn aiming to contribute to the development of cable supported glass façades.

Additionally, a commonly questioned issue is approached, this being the use of one-way vertical cable systems versus two-way cable nets. The one-way simpler system is verified to be relatively efficient for short walls, where the addition of horizontal cables does not add significantly to the stiffness of the wall. Cable diameter needed to be increased to provide the sufficient strength to the system.

Relevant findings were obtained regarding the influence of the type of glazing attachment on the system. The type of attachment affected heavily on the wind load that the system was able to bear and this presented constraints for the present case. Comparisons on stresses and deflection for the numerical models provided conclusions about the attachment systems.

Finally, recommendations and suggestions for future research work are given to encourage the use and continued development of such an interesting specialty.

Keywords: Structural glass, cable structure, point supported glass façade, numerical modelling, finite element analysis

Título: Numerical Simulation and Analysis of the mechanical behaviour of Cable supported Glass Façades

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El interés en maximizar la sensación de transparencia en fachadas de vidrio ha hecho que el uso de cables pretensados tome una importante función en los últimos años. Cuando los cables se configuran en forma de red y se pretensan proporcionalmente a su resistencia, crean un sistema estructural capaz de soportar fuerzas gravitacionales y laterales.

Con la introducción del pre-tensado y las estructuras de cables, se posibilita el diseño de fachadas modernas, de gran escala, peso ligero y gran transparencia. Es una estructura simple que ofrece la habilidad de cubrir grandes distancias sin la necesidad de elementos estructurales grandes y pesados en la fachada de vidrio. Además, brinda ventajas en cuanto a flexibilidad y sencillez de construcción, junto a una estética moderna que crea espacios perfectamente integrados entre los ambientes interiores y exteriores.

Es importante entender el comportamiento de cada componente y su influencia en el resto de componentes del sistema. El comportamiento de la estructura de cables bajo cargas y acciones influencia directamente en el diseño de la fijación y de los paneles de vidrio que forman el revestimiento del edificio.

Este estudio analiza el comportamiento mecánico de los componentes de este tipo de fachadas mediante la simulación numérica y el método de los elementos finitos, prestando especial atención al comportamiento de los paneles de vidrio ya que son las capacidades y carga del vidrio lo que define la base de diseño para cualquier sistema estructural de soporte.

Se presentan y analizan los distintos tipos de sistemas en función del tipo de fijación y de la distribución de cables horizontales y verticales.

Se aborda un tema de considerable relevancia en el desarrollo de esta tecnología, y es el uso de sistemas de cables verticales unidireccionales frente al uso de sistemas de cables bidireccionales horizontales y verticales formando una red. El sistema unidireccional se ha verificado como eficiente para fachadas de baja altura y larga anchura en las que la incorporación de cables horizontales no añade rigidez significativa a la fachada. Como contrapartida a la mayor simplicidad de este sistema, el diámetro de los cables se ve necesariamente incrementado para proporcionar la resistencia suficiente al sistema estructural.

El tipo de fijación ha supuesto una importante restricción en términos de carga de viento aplicada. El prototipo presentado se vio fuertemente influido por el tipo de fijación empleado, afectando en la capacidad de resistencia de carga de viento por parte del sistema estructural.

Finalmente, se proporcionan recomendaciones y sugerencias enfocadas a futura investigación del desarrollo de esta tecnología de vidrio estructural, con la esperanza de contribuir a dicho desarrollo y fomentar el uso y continua evolución de esta interesante materia.

Palabras clave: Vidrio estructural, estructuras de cables, fachadas de vidrio, modelización numérica, análisis por elementos finitos

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Chapter 1. Introduction

1.1. Motivation

The façade in a building is a vitally important component since no other building system impacts both the appearance and performance of a building as it does its skin. The façade is the enclosing membrane separating exterior elements and forces from interior occupied areas in a building, and it performs multiple functions. Primary façade functions include structural function, weather-tightness, energy efficiency, and accommodating building movements; the system needs to have the ability to support itself and the applied loads, keeping natural elements outside, performing high levels of reduced energy consumption, and properly accommodating movements in the building.

Exterior building enclosures of all kinds are seen in every city around the world. One of the main features in those facades is the material they use. Brick masonry, natural stone masonry, architectural concrete, metal framing and glass, are commonly used for different types of buildings, and they give a specific character to the building. In exterior building enclosure design, visual appearance is generally considered one of the major design components and each project might have specific needs and requirements.

A usual requirement in modern building facades is the search of transparency to create innovative aesthetic spaces perfectly integrated between indoor and outdoor environments.

The use of glass as a component of the building envelope has been increasing in the past decades and it will continue to do so due to its numerous advantages as a structural material. Transparency, light-weight, reduced energy consumption, low-cost maintenance, among many other advantages, make of glass facades an appealing system with varied application in the building marketplace.

This technology has matured over the years thanks to trials, tests, adaptations, development of methods and specifications, and the emergence of material suppliers, fabricators, and erectors responding to the increasing demand for structural glass facades.

Several research studies have been carried out in topics more or less related to the presented technology. Saitoh et al. (2001) evaluated the deformation and stress of a glass panel supported by point-fixed joints. Jan et al. (2001) performed static experiments to determine the load-carrying capacity of an armored glass panel. Wang (2002) analyzed the factors that affect the load-carrying capacity of a glass panel with a sunk-typed joint. Vyzantiadou (2004) proposed technological and morphological requirements of point-fixed joints. Feng (2006) and Feng et al. (2007, 2009, 2012) investigated the static and dynamic performance of a cable net facade as a function of glass panel stiffness.

At the same time, an increasing interest in the use of structural glass facades keeps growing. The success of previous projects featuring advanced glass façade designs have shown architects and engineers the increasing value of this technology. Its aesthetic and its ability to provide any degree of transparency based on required environmental considerations, make it a valuable design.

Yet this technology continues evolving and becoming more and more diverse, efficient, accessible and economical. This growing interest, together with the maturity of the technology, which shows promise for a significant continuity and growth of structural glass façade technologies, has encouraged the realization of this thesis to contribute to this evolution.

1.2. Objectives

With the objective to contribute to the evolution of structural glass technologies, this study presents an analysis of a particular façade system intending to provide insight on the mechanical behaviour of this kind of systems.

This study presents a structural cable supporting system which replaces conventional curtain wall systems in an increasing number of applications due to its advanced technology and high profile and transparency against other supporting systems.

The analysis of the presented façade as a whole system and the components breakdown aims to develop relevant conclusions and recommendations in regard to the use of cable supporting glass facades.

The research has been organized on the following basis:

- Gathering information on existing knowledge about cable supported glass facades and their behaviour, through a comprehensive review of bibliography and sources.
- Selecting a prototype as subject of study to represent a real project situation.
- Modelling a numerical simulation of the prototype in its configuration combinations and running a non-linear static analysis using the finite element method.
- Assessing the feasibility of the prototype by analysing and comparing the results obtained for the different situations.
- Drawing relevant conclusions and recommendations to contribute to the development of cable supported glass facades.

More specifically, the main components of these systems are approached, and variations of the system are presented and analysed based on the type of attachment used. Special attention is to be brought to the behaviour of the glass panels since it is the capabilities and loading of the glass that defines the basis of the design for any back-up structural system.

Additionally, a commonly questioned issue is also approached in this analysis. This is the use of one-way vertical cable systems versus two-way horizontal and vertical cable-nets. The later simpler system is believed to be relatively efficient for short walls, where the addition of horizontal cables does not add significantly to the stiffness of the wall. This theory will be tested for the chosen prototype.

Given that glass failure happens either in tension or by buckling, the present analysis is directed towards determining the highest stresses under load and determining the stability of the cable net.

1.3. Outline of the thesis

The thesis is divided into four chapters.

Chapter 1 presents an introduction to the topic of research explaining the main drivers and objectives of the thesis.

Chapter 2 puts the reader in context by offering background information on façade systems and describes in detail the different technology types of structural glass facades.

Chapter 3 presents the details about the analysis performed. After an exhaustive description of the numerical simulation models, obtained results are given and accordingly commented.

Finally, Chapter 4 provides conclusions on the research carried out, and offers recommendations and suggestions for future research work.

Chapter 2. Background

2.1. Building facades

The importance of visual appearance in building facades has already been discussed in the previous chapter, but building facades are more than just visual appearance. Their design is the integration of materials, material properties, and performance design principles, and it requires an understanding of the basics of materials, structural principles, natural elements, natural and human-created forces, thermal transfer and properties, and acoustics.

From a structural engineering point of view, each component within the exterior building enclosure system has certain and distinct structural properties. The structural capacity of a component is dependent upon material properties, size, thickness, orientation, method of attachment, and geometry. Components within a system will deflect from their own weight and the applied loads. When designing the enclosure system, it is fundamental to address the material, size of components, connections between components, and deflection when subjected to applied loads.

2.2. Structural glass facades

In the recent decades, a new façade technology has gradually emerged driven by the pursuit of transparency in the building façade: the structural glass façade.

The use of glass as a component of the building envelope has been increasing since its initial introduction as a building material, accelerating in the 20th century due to the development of high-rise steel framing systems and curtain wall cladding techniques. The use of this technology has changed most over the past two decades in terms of aesthetics and performance as well as in availability of structural systems and materials. The new designs have evolved since the primary attribute of glass and its transparency, and the structural properties of glass and its integration into the structural system have increased.

This new technology is characterized by highly crafted and exposed structural systems with long-spanning capacity, complex geometries, extensive use of tensile elements, specialized materials and processes, integration of the structure and the cladding system, and a complex range of design variables such as façade transparency, thermal performance and bomb blast considerations.

Structural glass facades integrate structure and cladding. The structural systems are exposed and therefore they are generally refined as a consequence. Structural glass systems are used in long-span applications where a sense of transparency and dematerialization of the structure are two predominant design goals. The pursuit of transparency has made designers use very refined tensional structural systems, where bending and compression elements in the structure are minimized or even eliminated when possible. This has been an efficient and sustainable strategy since less material is needed.

The structural glass façade is categorized by the structural system that it employs as support and by the glazing system used.

2.3. Structural support systems

Structural glass facades can be easily categorized by the structural system types used to support them. Each system type can have diverse applications according to their performance and aesthetic results, and they all provide elegant, minimalist and transparent façade solutions. These systems can be one-way spanning systems or two-way spanning systems, thus setting the elements' direction and distribution.

A generic selection of the most distinctive and used types of structural support systems is presented below. The systems are presented in order of increasing transparency, which at the same time means increasing complexity of the system and increasing cost due to complexity, despite the increasing material efficiency.

2.3.1. Truss systems

Various configurations and types of truss systems can be used to support glass facades. The most common application is the single truss design that is used as a vertical element. The trusses are positioned uniformly at a regular interval and its spacing is determined according to the glass grid. Truss design is a function of structural considerations such as span, loading, pitch, spacing and materials. It is common to combine other element types such as tension components in the truss design. Rod or cable elements can be used, and lateral tensile systems can help to stabilize the structure.

Truss systems that make predominant use of simple truss elements have a deflection criterion limit typically of L/175, where L is the span. Deflection limits are based on horizontal or vertical application, size of glass cladding panels, methods of glass attachment, and the connection of the truss to the primary building structure through support system attachments. Based on the deflection, the design needs to consider the material strength under deflection and also the influence of the system's deflection on the occupants of the building. Aesthetic considerations are also a primary design driver.

Figure 2.1. Three-dimensional tension truss system; Walter E. Washington Convention Center, Washington D.C., U.S.A.

2.3.2. Cable systems

Cable systems represent the ultimate in minimalist structural systems and they can provide optimum transparency when it is desired. The glass is supported by a net geometry of pre-tensioned cables, and connecting components lock the cables together at their vertices and also fix the glass to the net. Large pre-stress loads make it necessary to involve the façade design with the building structure design from early stages.

As we have previously mentioned, cable supported systems can have one-way or two-way spanning behaviour.

Figure 2.2. One-way cable system; China National Peking Opera Company, Beijing, China.

In one-way cable systems, also called cable hungs, the cable elements are tensioned vertically against top and bottom boundary structure.

When horizontal cables are added to the system, a two-way spanning system is created, named a cable net. The addition of the horizontal cables makes controlling system deflections easier, therefore requiring lessened pre-stress loads in the cable elements.

Figure 2.3. Two-way cable system; Time Warner Center, New York, U.S.A.

Cable net designs can be flat or pulled into double-curvature. The horizontal cables, which are aligned to a curve in elevation opposing curvature of the vertical cables in plan, are tensioned against the vertical cables forming a double-curved surface. The opposing curvature provides stability to the cable net, significantly limiting deflections under wind load and requiring lowe pre-stress forces in the cables. The grid is not orthogonal anymore, and trapezoidal shapes are created instead. This last characteristic results in more complicated requirements for the glazing system. If the corners of the trapezoids do not all lay on the same plane, the glass panels might require cold-forming during installation, therefore inducing a warping phenomenon to the glass panels. However, this can be avoided by careful design of the net geometry.

Figure 2.4. Double-curvature cable net system; Sea-Tac airport, Seattle, U.S.A.

Deflections are controlled by high pre-stress forces, and the general deflection criterion ranges L/45 to L/50 for cable nets. This allows for significant deflections under wind load and produces a highly flexible system. One-way cable hungs are typically limited by a lower deflection criterion of L/35.

Cable nets were first developed and popularized as structural systems by Frei Otto in the 1960s and 70s. They were first applied as a supporting structural system in a glass facade in 1993 for the Kempinski Hotel Airport in Munich, Germany, by the architect Helmut Jahn together with the engineering firm Schlaich Bergermann. This project awoke a widespread interest in this structural form in glass facade applications and it has been widely applied to glass facades in recent years due to its elegant appearance and fast construction. A significant recent development in terms of achievable size of the cable-net wall is the New Beijing Poly Plaza in Beijing, China, completed in 2005.

Figure 2.5. Kempinski Hotel Airport Munich, Munich, Germany.

Figure 2.6. New Beijing Poly Plaza, Beijing, China.

2.3.3. Glass fin systems

These systems are referred to as high-transparency structures, and they represent a special case of structural glass façade technology. They are often used in all-glass buildings and they constitute a stand-alone structural glass system that requires no metallic supporting structure.

The vertical glass supports, which are called glass fins, are set perpendicular to the glazing membrane providing lateral support to the system to resist wind load. Glass self-weight and applied wind loads are transferred up to the primary building structure above. Fins are most typically suspended. They are made of tempered glass, and their dimensions, in terms of height, are limited by the maximum length that the producer can provide considering the process in the tempering oven. Sometimes, a single fin is not long enough to support the span and then fins must be spliced.

Figure 2.7. Glass fins system; Hotel Sheraton Mirage, Gold Coast, Australia.

This form of glass façade dates back to the 1950s and it was first used at the Maison de la Radio in Paris where glass fins were set perpendicular to two-story suspended glass plates providing lateral stiffness. It was later popularized in England in 1972 with the curved façade at the Willis Faber & Dumas Building designed by Foster Associates, which became one of the first examples of an entirely frameless glass façade. This project served as an inspiration and the diffusion of the glass fin technology extended throughout Europe and America.

Figure 2.8. Maison de la Radio, Paris, France.

Figure 2.9. Willis Faber & Dumas Building, England, U.K.

2.4. Glazing systems

Glazing systems have two functions in the façade. The first function is to provide weather seal for the façade. And the second function is to fix the glass to the supporting structure, which can be done in different ways and defines the glazing system used. A selection of alternatives is presented below categorized by the existance or lack of a framing element.

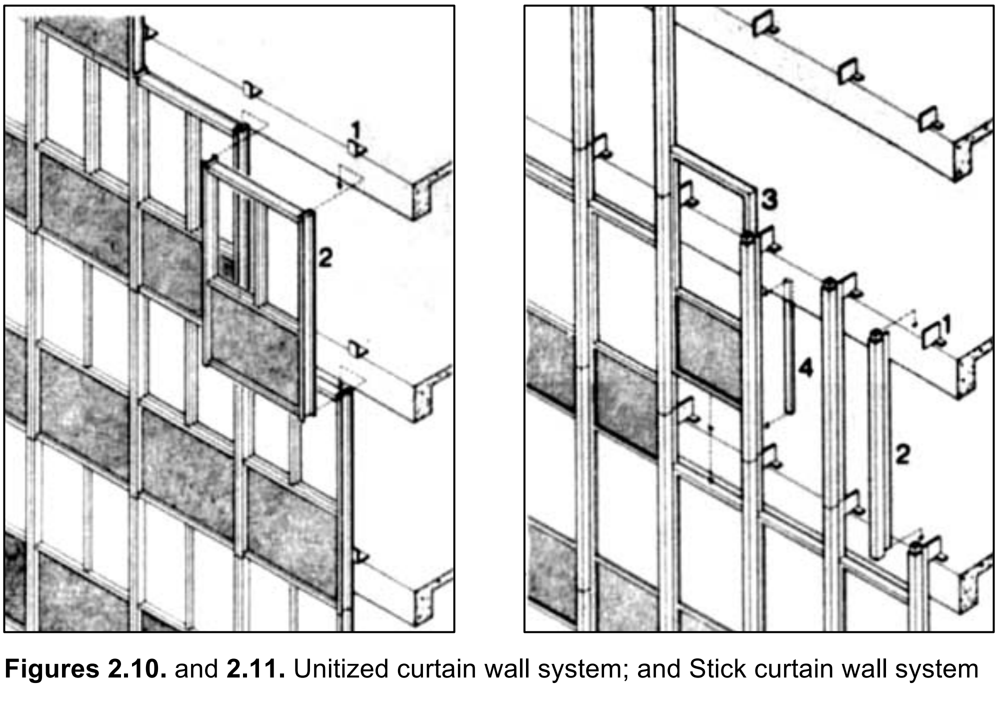
2.4.1. Framed systems or Curtain wall systems

Framed systems support the glass continuously along two or four sides. There are two general categories: stick systems and unitized systems. The difference between stick and unitized curtain walls is the method of construction of the framing system.

Stick systems generally have their components prepared in a factory, shipped to the jobsite, and then erected piece by piece on-site.

Whereas unitized systems have their components prepared and assembled in the factory and then they are shipped to the jobsite as a completed unit. Once in site, each unit is connected together to form the façade.

Stick systems take longer to assemble on-site and might present quality control issues. On the other hand, unitized systems take longer to manufacture in the factory but the erection of the façade on-site is accelerated and quality control can be monitored strictly.



Figures 2.10. and **2.11.** Unitized curtain wall system; and Stick curtain wall system

However, framed systems are rarely used in structural glass facades due to the pursuit of transparency and dematerialization of the structural glass façade design. The frames in curtain wall systems need to provide structural integrity for the units in order to be resistant to handling both in the factory and the site, and this makes it harder to integrate the structural system and the cladding to create a sense of total transparency. Sometimes, however, the balance between aesthetics and efficiency in a certain project might make them a good choice.

2.4.2. Frameless systems or Point-fixed systems

Frameless systems are the most frequent in structural glass facades. They utilize glass panes that are fixed to the structural systems at discrete points, usually near the corners of the glass panel. And they are commonly called point-fixed systems. The glass is directly supported without the use of perimeter framing elements, so there is no continuous edge support as in conventional curtain walls.

Glass panes in point-fixed glazing systems can be either bolted or clamped with components providing attachment to the supporting system.

2.4.2.1. Point-fixed bolted systems

The point-fixed bolted glass system is the most popular one within structural glass façade designs. This type of mechanical attachment consists of a fitting that accommodates a bolt through a hole drilled in the glass panel and ties it to the supporting structure. They are made of stainless material.

Figure 2.12. Point-fixed bolted device, spider model (Kin Long)

The glass must be designed to accommodate bending loads and deflections resulting from the fixing method. Requiring the fabrication of 12 holes per panel in insulated-laminated glass panels might represent a cost constraint on some projects. It is considered the most expensive glazing system.

Furthermore, when using insulating laminated glass panels, i.e. multi-layer glass panels with an air cavity between the layers, this system presents an additional problem when drilling. The hole needs to be sealed around so that it does not compromise the air cavity of the panel. A ringed spacer has been developed in order to seal around the fixing component and solve the problem in laminated glass units.

Figure 2.13. Routel with Ring Spacer for drilled insulated glass (Kin Long)

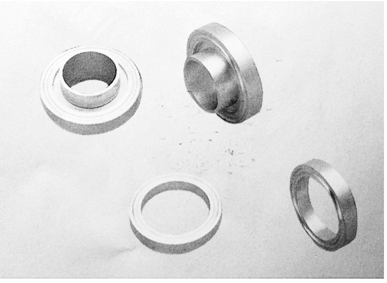


Figure 2.14. Ring Spacer for drilled insulated glass (Kin Long)

Figure 2.15. Point-fixed bolted system; New International Bangkok Airport, Bangkok, Thailand.

2.4.2.2. Point-fixed clamped systems

Figure 2.16. Point-fixed clamping device

The previous method of point-fixing requires drilling the glass panes, which entails disadvantages. An alternate strategy is to clamp the glass instead of drilling holes in it for bolting. The glass is set into a specially designed clamp component tied to the supporting structure. A cover plate is then attached over the outside corners of the glass, clamping the glass at the corners. Neoprene pads are used on both faces of the clamps to protect the glass. This is a frequently employed method on cable nets.

Figure 2.17. Point-fixed clamped system; Time Warner Center, New York, U.S.A.

2.5. Point-fixed Cable supported system

After an introduction on different glass façade systems, this section presents the system of study in this thesis which is the cable supported glass façade system.

Cable supported glass walls are composed of three primary components: cables, glazing panels and glazing support attachments. Gravitational loads from the glass elements are carried through the attachment nodes to the vertical cables, and transferred up to the main structure in the base building above. Lateral deformations due to wind loading are resisted by the tendency of each cable to return to its straight line configuration between supports.

It is important to fully understand each component's performance and its associated influence on the other components in the system. The cable system behaviour under loads and deflections directly influences the design of the glass attachment and therefore the glass plates forming the cladding.

Cable systems are naturally flexible under lateral loading such as wind loading, so the critical goal when designing is to limit its deflection. This is done through adjusting the axial stiffness of the cables and through pre-tension. Typical deflection limits under a 50-year return wind loading condition ensures protection to the integrity of the glass and the sealants, and minimizes the perception of movement for the occupants in the building.

2.5.1. Cables

Each cable in the system is composed of individual cold-drawn wires that are twisted together in arrangements that can vary, being the most basic one the wire strand. A strand consists of individual wires twisted around a central core wire. The wire rope is then made by twisting many strand cables around a central core strand. Cables can have various configurations depending on the number of strands and wires they contain.

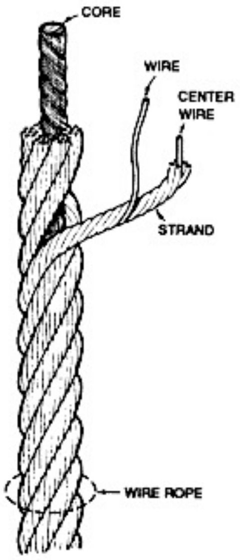


Figure 2.18. Wire rope diagram (Saftey Sling 2005)

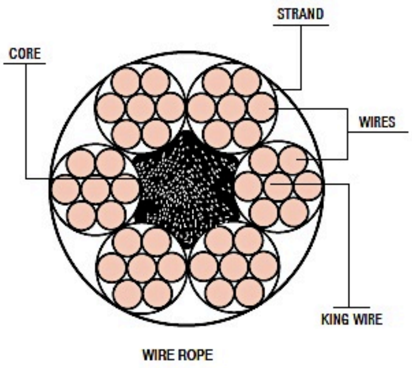


Figure 2.19. Wire rope cross-section (Usha Martin)

Strands used for tension cables in façade systems are spiral strands, and the configuration of the strand is designated by the number of wires in one strand, i.e. 1x19 means there are 19 wires in every strand.

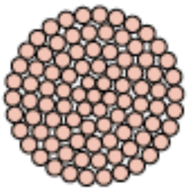


Figure 2.20. Spiral strand cross-section (Usha Martin)

Cables are made of either stainless steel or galvanized steel and they are normally treated to be used in cable-net applications because they are exposed. Since cables are on the interior of the building, corrosion is only an issue during construction.

2.5.2. Glazing panels

Glass is employed as a structural material in these systems, but it behaves in a very different way from other structural materials such as steel or aluminium which are more familiar. Glass does not yield, it fractures and its failure can only be predicted by statistical or risk-based prediction.

There are many types of glass that are used for building enclosures. Glass can be annealed, heat-strengthened, laminated, wired, patterned, tinted, reflective coated, low-iron, among many others.

In terms of glass configurations, there are three basic types of glazing: monolithic glass, laminated glass and insulating glass. Monolithic glass is the common single sheet of glass; laminated glass consists of an assembly of two or more plies of glass bonded together with an interlayer material such as PVB or similar; insulating glass, on the other hand, is formed by two or more lites of glass separated by a spacer that creates an air cavity and it is hermetically sealed around the perimeter.

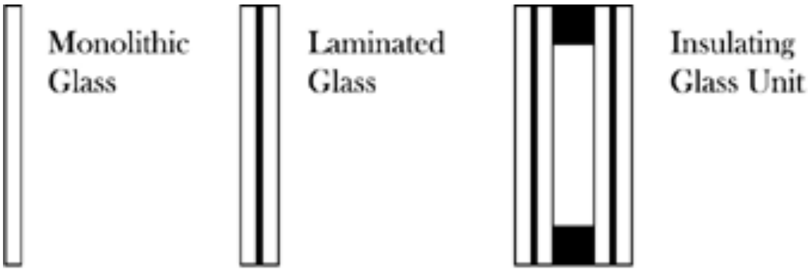


Figure 2.21. Glass configurations

Additionally, glass is characterized by the strengthening treatments that it receives. Annealed flat glass or tempered glass is the common tranparent glass, surfaces of which are flat and parallel so that they provide clar, undistorted vision and reflection. Annealed glass is liable to crack under heavy loading, under impact or under thermal shock.

Heat-strengthened or toughened glass is made of a safety glazing material produced by subjecting annealed glass to a heat strengthening treatment. The glass is subjected to a process of heating and rapid cooling which induces high compression in the surface and a compensating tension in the centre. This increases the strength of the glass, and higher applied loads can be resisted before the outer surface fractures. Because of this pre-stressing, heat-strengthened glass is less liable than annealed glass to break as a result of heavy loading, impact or thermal stress. If it should break, it fragments into comparatively harmless pieces.

In cable-nets, it is common to employ laminated glass as a stronger safety measure against breakout. Laminated glass features two or more panes of glass with an interlayer of reinforcing material between each pane that is permanently bonded to the glass panes and which is able to absorb impact shock, holding the glass in place and preventing extensive fall of glass fragments. However, this type of glass presents a further challenge when used in point-fixed bolted systems. Bolted systems require drilling, which means that the various layer of laminated glass are drilled, compromising the air cavity of the panel. Therefore it is necessary to incorporate a riged spacer to seal the hole instead of ordinary spacers.

2.5.3. Glazing support attachments

Glazing panels are attached to the cable net by fittings, which also connect to the cable intersections. The fittings provide support at the corners of the glass panels creating what is called a point-fixed glass system. The glass panels are fastened back to the support structure and the loads incident on the glass are transferred through the fittings into the structures.

The fittings are either bolted or clamped to the glass panels providing attachment to the structural system. The main difference between bolted and clamped devices is the way in which they are connected to the glass panels. Bolted attachments such as spider systems, are connected to the glass panel by a metal bolt located at one corner of the panel, requiring holes drilling. Clamped devices use metal fasteners to clamp the glass panel to the joint, avoiding drilling.

Figures 2.22. and **2.23.** Point-fixed bolted device; Point-fixed clamping device. (Kin Long)

Chapter 3. Numerical Analysis

3.1. Analysis method

Before modelling the numerical simulation of the prototype, a description regarding analysis method used is given to understand the solving process.

3.2.1. Nonlinear behaviour

Despite all the advantages discussed at the beginning of this study, the high geometric non-linearity of cable structures has been a potential threat to the stability of such cable supported glass facades.

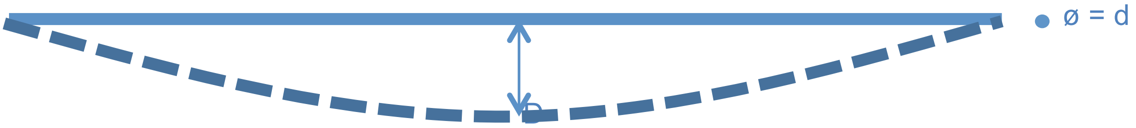
Cable nets are a basic form of tension structures. The high degree of flexibility of such structures leads to a particular behaviour that is considered nonlinear.

When studying the fundamental difference between linear and nonlinear analysis, it is the term “stiffness” that defines it. Stiffness, complimentary concept of flexibility, is a property of an element that characterises its response to the applied load, i.e. when a structure deforms under a load, its stiffness might change. If the change in stiffness is small enough, it makes sense to assume that neither the shape nor material properties change at all during the deformation process, leading to the fundamental principle of linear analysis. However, if stiffness changes during the deformation process, as in cable elements, the assumption of constant stiffness needs to be abandoned, leading to a nonlinear behaviour.

Now, if these changes in stiffness come only from changes in shape, as in cable elements, the nonlinear behaviour is defined as geometric nonlinearity.

In the case of loaded cable nets, large deformations are observed causing such geometrical changes in stiffness. According to nonlinear analysis report by 3D CAD Design Software SolidWorks, a general rule of thumb that might suggest conducting a nonlinear geometry analysis is the comparison of deformation (D) and dimension (d) of the element. If the deformations are larger than 1/20th of the part's largest dimension, a nonlinear geometry analysis is to be conducted. The deformation of the cable is expected to be much greater than its diameter.

$$D \gg d$$



If we focus in the glass plates' structural behaviour, the general rule of thumb to assess whether linear or non-linear theory must be applied is the lateral deflection of the plate being more than half its thickness. Considering regular thickness dimensions of glazing systems for facades, the deflections in the cable-supported glass wall are also to be much greater that the former. Therefore, large deflection non-linear theory comes into play, to take account of the membrane stresses that are set up.

3.2.2. Strand7: finite element analysis system

As previously mentioned, observations in this study are obtained by modelling numerical simulations of a real case. The models are solved using finite element analysis (FEA) software called Strand7.

Strand7 is a FEA system developed in Australia with a general purpose for structural analysis and heat transfer. It comprises pre-processing, post-processing and solver functionality.

The use of finite element modelling allows us to predict the behaviour of the non-built structure under loading conditions, and provides a trial and error method that can be repeated and changed without costs until the desired behaviour is achieved.

Strand7 features a range of solvers including all the basic solver options and some advanced configurations. A nonlinear static solver was used for the analysis of the present thesis. Three types of nonlinearities including geometric, material and boundary nonlinearity are performed by the nonlinear static solver in Strand7.

The solver performs the following steps:

1) Initialises the nodal displacement vector $\{d\}$, element stress, stair σ_e, ε_e, etc.

2) Sets the current load increment. The Strand7 nonlinear static solver uses an algorithm based on modified Newton-Raphson method. In this method, the load is subdivided into a series of load increments; and the load increments can be applied over several steps.

3) Calculates and assembles the element stiffness matrices, equivalent element force vectors and external nodal force vectors. Material temperature dependency is considered in the stiffness calculation. The current geometry is used when geometric nonlinearity is considered. Constraints are also assembled in this process and the constant terms in the enforced displacements and shrink links are combined and applied.

At the end of this assembly procedure, the following linear equation system of equilibrium is formed:

$$[K(d, \sigma_e, \varepsilon_e)]\{\Delta d\} = \{R\}$$

Where $[K(d, \sigma_e, \varepsilon_e)]$ is the current global stiffness matrix,

$\{\Delta d\}$ is the displacement increment vector, and

$\{R\}$ is the global residual force vector

4) Solves the above equation for $\{\Delta d\}$.

5) Updates the total nodal displacement vector.

6) Checks convergence

Displacement norm $\frac{\|\Delta d\|}{\|d\|} < \varepsilon_d$

Residual force norm $\frac{\|R\|}{\|F_0\|} < \varepsilon_r$

Where ε_d and ε_r are convergence tolerances on displacement and residual force,

$\|\Delta d\|$ and $\|d\|$ are norms of incremental and total displacement vectors,

$\|P_o\|$ is the norm of the residual force vector at the first iteration of each time step, and

$\|R\|$ is the norm of the residual force vector in the current iteration.

7) If both of the convergence criteria are satisfied, it starts the next load step or stops at the last load step. If either of the criteria is not satisfied, it continues the iteration.

3.2. Cable supported glass façade prototype

The studied façade consists in 3m x 1.25m glass panels as shown in Figure 3.1, with a thickness of 15mm. Stainless steel cables subjected to a initial pre-tension support the cladding wall. And the whole facade prototype is assumed 15m wide and 10m tall vertically spanning floor-to-floor as shown in Figure 3.2.

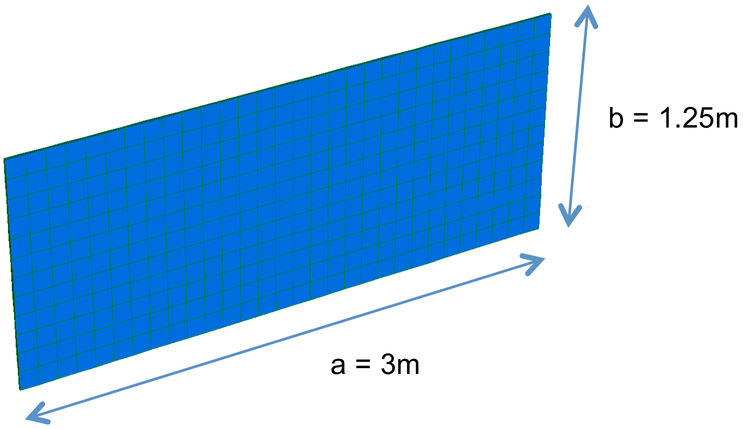


Figure 3.1. Glass panel dimensions (Strand7)

The prototype is based in a possible real project where a part of the façade features a module like the one we present and it might compose the entrance to a building lobby with a clear height of 10m spanning from ground level to the top of the lobby possibly including a mezzanine. This is a typical disposition for building entrances such as hotel halls for instance. As shown in the project cases presented in the previous Chapter describing the background, many building façades are composed of different façade systems, e.g. Figure 2.6. New Beijing Poly Plaza where the cable net façade is only an element integrated in the rest of the building enclosure. According to this, the present prototype simulates a cable supported glass façade module that is anchored at its boundaries to the main building structure, and that might serve as the front façade to a building lobby, and it is possibly integrated in many kinds of building enclosure.

The glass facade prototype has been tested conducting different models, each one defined by its differences in the type of attachment.

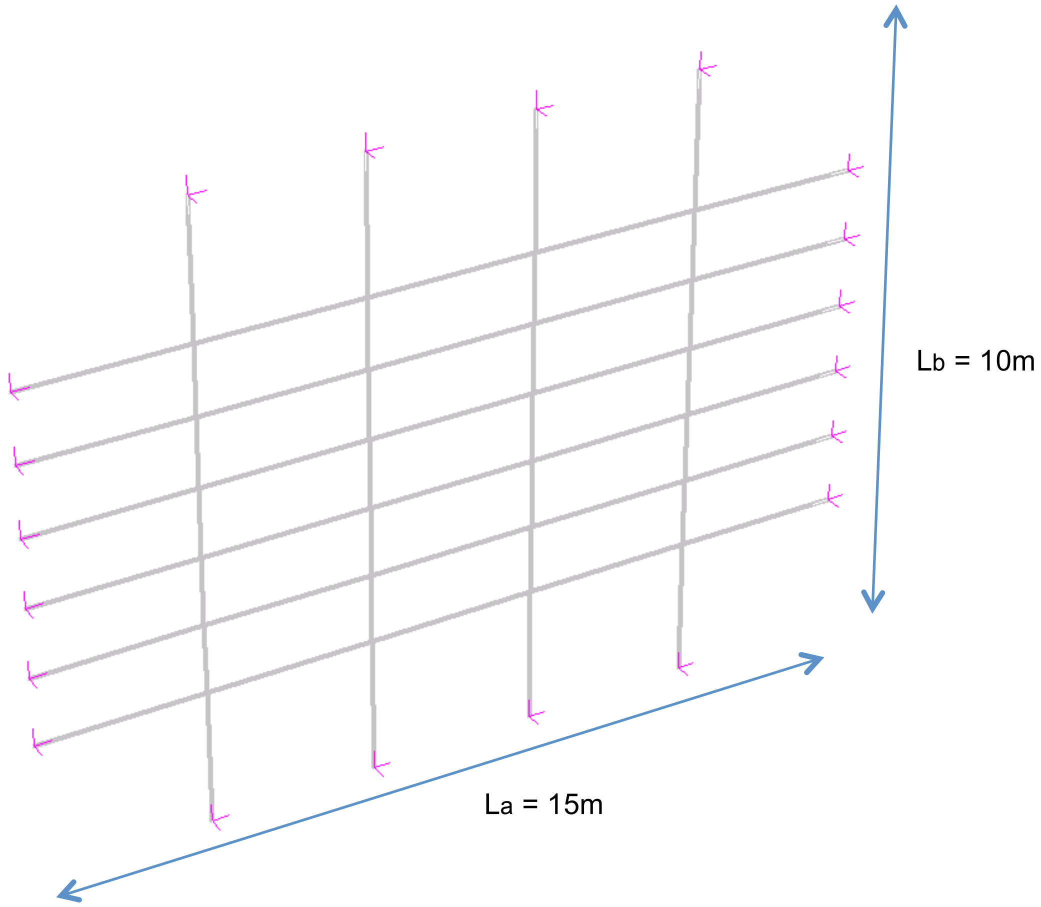


Figure 3.2. Cable-net dimensions (Strand7)

Glazing support attachments form the interface between the glazing panels and the support structure. The attachments provide the structural inter-connection and they allow relative adjustment in position. The attachments can take many forms but the most common for bolted attachments are spiders, and clamping devices for clamped attachments. This study wants to analyse the difference in behaviour of the glazing panels depending on their attachment system.

Additionally, a commonly questioned issue is also approached in this analysis. This is the use of one-way vertical cable systems versus two-way horizontal and vertical cable-nets. The later simpler system is believed to be relatively efficient for short walls, where the addition of horizontal cables does not add significantly to the stiffness of the wall. This theory was tested for the present prototype and the results led to some interesting conclusions regarding this system that are presented at the end of this report.

Combining these two variables -glass attachment and cable-supporting system- four models were developed.

- Model I: Two-way cable-net with clamped attachment
- Model II: Two-way cable-net with bolted attachment
- Model III: One-way vertical cable system with clamped attachment
- Model IV: One-way vertical cable system with bolted attachment

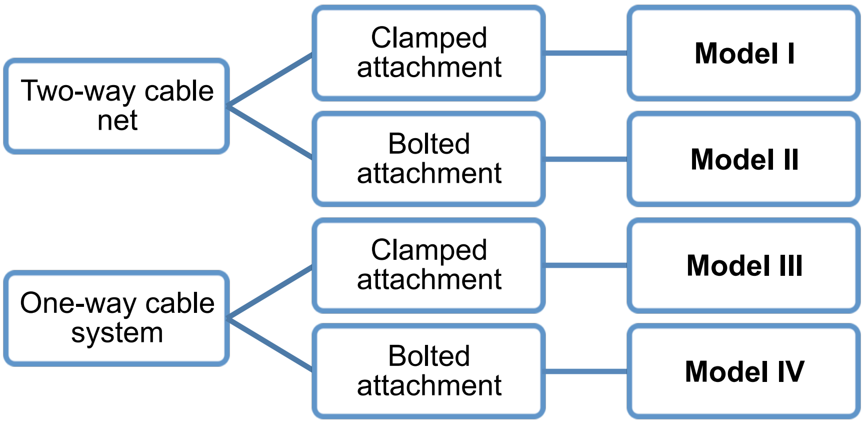


Figure 3.3. Models summary

Note that anchorages have not been considered in this study. Anchorage assemblies transfer the enclosure loads to the primary buildings structure and accommodate the primary building structural system's deflections and movements. One-way cable and cable net systems require two types of support connections to the primary structure. In the first place, a connection called dead head is defined as the connection that accepts and transfers loads from the system into a non-adjustable connection. Dead heads can be fixed or pinned to allow rotation, and they are usually located and installed prior to the installation of the cable connection. On the other hand, an adjustable connection is also defined and it accepts and transfers loads from the structural glass system, and it allows flexibility and has the ability to tune the tension in the cables according to pre-specified forces. Cable systems' deflections are accommodated by the cable flexing and rotation at the connection without weakening the end connections. Figures 3.4. and 3.5. show an example of adjustable support system connection and the detailed components of such connection. Due to the complexity of structural glass systems, the considerations and design of these assemblies require a high level of scrutiny and specialty that goes beyond what this study wants to cover.

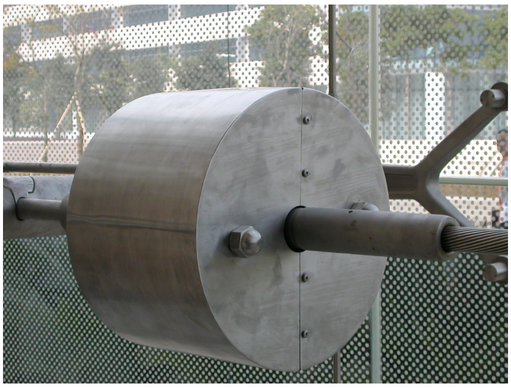


Figure 3.4. Adjustable support system connection (MFT)

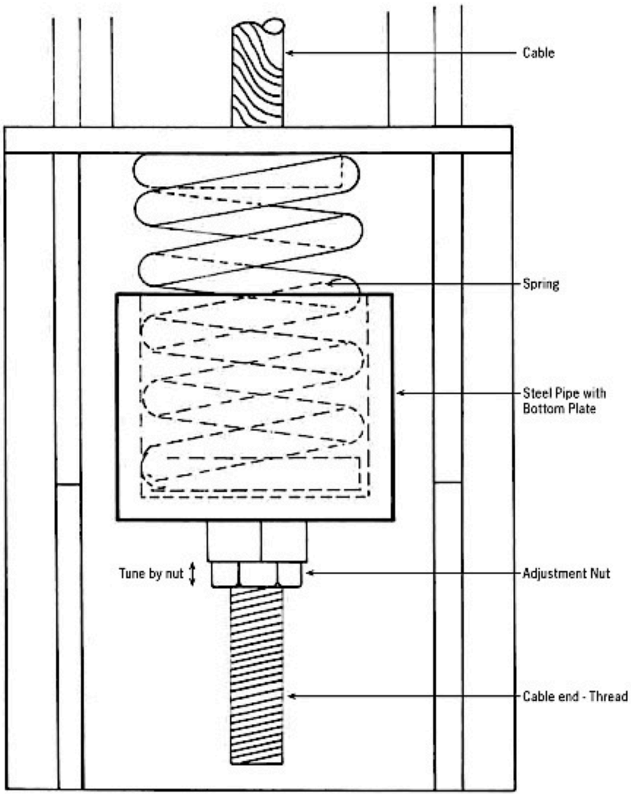


Figure 3.5. Adjustable connection detail

3.3. Loads

Facade cable nets have to carry their own weight together with that of the glass, but their most important function is to resist the bending effect of horizontal wind pressure and suction.

A wind load was applied to the model acting on the glazing panels. The structural function of the glazing attachments is then to transfer the applied wind load acting on the glazing panels and the self-weight of the glazing panels to the support structure. The load was applied to the model in 3 load increments of 0.25, 0.5 and 1.

The supporting cable-net, which is formed of tension elements, supports and stabilizes the glass facade through the resistance to deformation of the pre-tensioned net. So gravitational loads from the glass elements are carried through the attachment nodes to the vertical cables and up to a transfer structure in the base building above; and, on the other hand, lateral deformations due to wind loading are resisted by the tendency of each horizontal and vertical cable to return to its straight line configuration between supports.

Each cable element is pre-tensioned according to resisting strength requirements, and, through adding the proper pre-stress to the cables, rigidity is formed so as to resist the exterior load. A pre-load was applied to the cable elements in the model according to the properties of the cables.

Since these pre-stressing loads applied to the cables are transferred to the base building structure around the perimeter of the wall, they become a significant contribution to the overall design of the main boundary structure, making it extremely important to design a boundary structure with the ability to undertake these strong tensile forces from the beginning.

The cable-net system has been checked to meet the required structural behaviour. A static analysis of the finite element model of the cable net structure under wind load was conducted to assess whether the cable net structure met the requirements for strength.

Note that other load actions such as thermal and seismic effects have not been contemplated because they are considered to be out of the scope of this study. However, they are relatively easy to apply to the models run by the finite element analysis software used. This is done by simply adding the seismic acceleration in the horizontal direction. As for the thermal effect, it can also be included when applying the load to the systems.

3.4. Performance criteria

The supporting system is designed with stiffness as the primary criterion. The stiffness design criterion, which is stated in terms of deflection, varies depending on the material being supported, joinery size, system assembly, among others. Stiffness and deflection are usually defined as D = L/number, where D is the deflection, L is span length or distance between points of support or anchorage, and the "number" is dependent on the cladding material being supported or the desired criterion established as the maximum bending (deflection) allowed.

According to Patterson (2011), in-service deflection limits under a 50-year return wind loading condition are typically set to **L/50** for two-way cable-nets and **L/35** for one-way cable systems (with L corresponding to the shortest span passing through the considered point) to protect the integrity of the glass and sealants and to minimize a perception of movement by the building's occupants. Deflection can be limited through adjusting axial stiffness of the cables and pre-tension.

It is desired to design a cable net structure that satisfies all displacement and stress performance criteria with as small a level of pre-tensioning as possible, because higher pre-tensioning requires more substantial cables, stronger connections and stronger boundary structures.

Cable Diameter (mm)	Reference Configuration	Steel Wire Diameter (mm)	Sectional Area (mm^2)	Minimum Breaking Strength (kN)	Modules Elasticity (10^5N/mm^2)
8	1x19	1.60	38.20	43.87	1.30±0.10
10		2.00	59.69	68.55	
12		2.40	85.95	98.71	
14		2.80	116.99	134.35	
16		3.20	152.81	175.48	
16	1x37	2.29	152.39	175.00	
18		2.57	192.15	218.16	
20		2.86	237.22	269.33	
22	1x61	2.44	286.27	325.02	
24		2.67	340.69	386.80	
26		2.89	399.84	453.95	
28		3.11	463.71	526.48	
30	1x91	2.73	531.60	603.56	
32		2.91	604.85	686.71	
34		3.09	682.82	775.24	
36		3.27	765.51	869.12	
38		3.45	852.93	968.37	
40		3.64	945.07	1072.99	

Table 3.1. Parameters and mechanical properties of stainless steel tension cables, by KIN LONG Construction Hardware Expert

On the other hand, stress limitation in both cable elements and glass panels comes defined by their mechanical properties. Allowable stress in a cable is determined by its minimum breaking strength over its sectional area, applying a safety factor of 2.0. Typical stainless steel tension cable parameters and mechanical properties are shown in Table 3.1.

Regarding stress limits for the glass panels, we refer to requirements on international glass codes and standards and the following information has been compiled in Table 3.2. Note that not all codes provide guidance or requirements on stress limits, but indications on Annealed glass, Heat-Strengthened (HS) glass and Full-Toughened (FT) glass are stated in the Chinese (PRC, People's Republic of China) and Australian code, and consequently, a stress limit for HS glass surface compression of **58 Mpa** has been adopted in this project.

COUNTRY	USA	UK	PRC	Australia
Glass Design Code	ASTM E1300	BS6262 2 2005	JGJ102-2003	AS1288
Permissible/Limit State	Permissible	Limit State	Limit State	Limit State
Wind Load Duration	3 sec	60 min	10 min	3 sec
Stress Limits Provided	No	No	Yes	Yes
Laminated - Load Share	Equivalent thickness	No	Yes	Yes
Insulating - Load Share	No	No	Yes	Yes
Edge Stress Limits	Yes	No	No	Yes
Annealed Stress Limit	No	No	2828psi (19.5MPa)	4786psi (33MPa)
HS Stress Limit	No	No	-	8412psi (**58MPa**)
FT Stress Limit	No	No	8528psi (58.8MPa)	11893psi (82MPa)

Table 3.2. International Glass Codes Comparison

3.5. FE-Modelling

According to the schematic layout presented, the studied façade prototype was modelled using the finite element computer program Strand7.

Glass panels were described by means of 360 four-node shell elements for bolted type models, and 432 shell elements for clamped type models due to the demanded matching geometry with the round-shaped clamps. Pretensioned cables were modelled in the form of truss elements having a cross-section area equal to half the nominal one. There are 10 cables in the prototype, which were subdivided in a total number of 58 cables in the model.

Point-fixed bolted devices were modelled as beam elements conforming the four-hole crossbar lined to the glass panels and the supporting bar that connects the crossbar to the pretensioned cables, resulting in a rigid connector for the cladding wall. 5 beam elements compose a single spider type attachment in the model.

While bolted devices were modelled with beam elements, point-fixed clamped devices were modelled by means of brick elements instead, to conform the clamp attachment in the model. A single clamp is modelled by 277 brick elements, of which, 181 conform the stainless steel device and the other 96 bricks conform the neoprene pads. The supporting bar that connects the clamp to the pretensioned cables is modelled in the form of a beam element as in the previous attachment type.

All nodes were opportunely constrained in accordance with the expected behaviour of the façade. Only U_z translational displacements were allowed for the cable nodes. Fixed conditions were applied to the boundary nodes of the cable net, where the cables are supposed to be anchored to the main building structure. As for the connectors, rigidly connected beams were joined together by means of a restraining weld connector able to provide a fully bonded connection between the relative displacements and rotations of the spider components ($u_x = u_y = u_z = 0$ and $r_x = r_y = r_z = 0$). On the other hand, the modelled spiders allow the glass panels interacting with the vertical cables by means of join connectors, prohibiting possible relative displacements in the interested nodes ($u_x = u_y = u_z = 0$).

Link elements were used in clamped models to define the relationship between nodes in the glass-neoprene contact. Pinned links were used to connect these nodes together by coupling the translational degrees of freedom transferred from the clamp to the glass panels. Additionally, attachment links were used to connect the clamp brick elements and the beam element representing the supporting bar that connects the clamp to the pretensioned cables. Attachment links are used to connect dissimilar elements such as a beam end and a brick face like in the present case.

Summing up, the four previously mentioned models that were analysed were described by:

- **Model I**: Two-way cable-net with clamped attachment modelled by a total number of 18439 nodes, 82 beam elements, 6480 plate elements, 6648 brick elements, and 2496 links.
- **Model II:** Two-way cable-net with bolted attachment modelled by a total number of 6119 nodes, 142 beam elements, and 5400 plate elements.
- **Model III**: One-way vertical cable system with clamped attachment modelled by a total number of 18427 nodes, 52 beam elements, 6480 plate elements, 6648 brick elements, and 2496 links.
- **Model IV**: One-way vertical cable system with bolted attachment modelled by a total number of 6107 nodes, 112 beam elements, and 5400 plate elements.

It is important to notice that, in bolted attachment models, the holes in the glass panels have not been modelled in this numerical simulation. Instead, one node of the glass panel located at 100mm from both sides of the corner is connected to the attachment device and represents the point where each of the four bolts should be drilled. Simulation of real holes in the glass requires a complete additional study with a high level of detail. Some recommendations are given at the end of this report regarding holes and drilling in point-fixed bolted glazing systems.

3.5.1. Material properties

Material properties and assumed constitutive models in the numerical simulations carried out with the FE-models are presented below.

	Young's modulus (N/m^2)	Poisson's ratio	Density (kg/m^3)	Behaviour
Glass panes	7×10^{10}	0.21	2700	Linear elastic
Stainless steel (cables)	1.3×10^{11}	0.28	7800	Linear elastic
Stainless steel (connectors and devices)	2.1×10^{11}	0.27	7800	Linear elastic
Neoprene pads	2×10^{9}	0.49	1700	Linear elastic

Table 3.3. Material properties (Strand7)

Constitutive models describe the behaviour of a specific material under influence of external forces. Glass is assumed as an isotropic linear-elastic material. Stainless steel for the cables and attachment connectors is also assumed to behave linear elastically. And finally, neoprene pads on both faces of the clamps, which work to protect the glass, are synthetic rubbers that have been assumed to have a viscous response that obeys the Neo-Hookean rubber model and has an elastic behaviour. The material properties are summarized in Table 3.3.

3.6. Analysis

Numerical analyses were performed on the FE-models of the façade prototypes to study the behaviour of the glazing system subjected to the applied loads and to highlight the structural benefits involved by the use of each attachment system.

In order to obtain the optimal design for each system, different parameters were subjected to trials until the model performed a successful solution. These parameters are the wind load applied to the glazing panels, and the cable diameter.

3.6.1. Two-way cable-net models

As previously discussed, deflection criterion for flat cable-nets is L/50, where L is the wall's shortest span and in our case it is the vertical span which is Lb = 11385mm. The models have been checked to meet this limitation of L/50 = De_c = 227.7mm.

A typical cable diameter of **22mm** was used. With a reference configuration of 1x61, according to manufacturers' provisions presented in Table 3.1, the cable's sectional area is 286.27mm^2 and cable minimum breaking strength is 325.02kN. After applying a safety factor of 2.0, the cable allowable stress is defined as

$$\sigma = \frac{325.02/2}{286.27} = 567.5\ \mathrm{MPa}$$

Cables were previously pre-stressed with a load proportional to its breaking strength. Providing 30% of the factored down minimum breaking strength, the pre-tension applied to the cables is

$$30\%(325.02/2) \approx 50\ \mathrm{kN}$$

According to the criteria above mentioned, each model has been designed to its optimal performance depending on its attachment type and to meet displacement and stress requirements avoiding failure of the system.

Two-way cable net models are named Model I and Model II.

3.6.1.1. Clamped attachment

The two-way cable net featuring the clamping device, substantially reduced the amount of wind load that the wall was able to bear considering the fixed geometric conditions.

Initially, a wind load of 3kPa was applied to the glazing panels, resulting in the failure of the numerical model. The analysis of the model was then run again with an applied wind load of 2kPa, but again the façade model was unable to withstand the rotation and stresses developed around the attachments caused by the combination of loads. The model was tested with decreasing wind load values until the bearable amount was reached. Clamped systems were found to withstand wind loads up to **0.2kPa**.

This two-way cable net system with clamped attachments was analysed in Model I.

3.6.1.2. Bolted attachment

The same process was carried out for the two-way cable net model featuring the bolted attachment type, however, this system was able to withstand wind loads up to **1kPa** due to its higher tolerance connections.

It is essential to remember that the holes in the glass panels have not been modelled in this numerical simulation. Instead, one node of the glass panel located at 100mm from both sides of the corner is connected to the attachment device and represents the point where each of the four bolts should be drilled. Simulation of real holes in the glass requires a complete additional study with a high level of detail. Some recommendations are given at the end of this report regarding holes and drilling in point-fixed bolted glazing systems.

The two-way cable net system with bolted attachments was analysed in Model II.

3.6.2. One-way cable system models

Deflection criterion for one-way cable systems is L/35, being L the vertical span equal to Lb = 11385mm. Maximum displacement observed at the centre of the wall was checked to meet deflection requirements of L/35 = De_c = 325.3mm.

A higher pre-stress load is required to resist the acting loads in one-way cable systems. Cables with **30mm** diameter and 1x91 configuration provide higher breaking strength. Allowable stress in the cables is σ = 567.7MPa considering a sectional area of 531.6mm2, a minimum breaking strength of 603.56kN, and a safety factor of 2.0.

$$\sigma = \frac{603.56/2}{531.6} = 567.7 \text{ MPa}$$

Cables were pre-stressed with a load proportional to its breaking strength. Providing 30% of the factored down minimum breaking strength, the pre-tension applied to the 30mm-diameter cables is

$$30\%(603.56/2) \approx 90.5\ \mathrm{kN}$$

It can be observed that one-way systems will require higher pre-stressing requirements than two-way cable nets.

When we remove the horizontal cables, a simpler system of only vertical cables is modelled with one main requirement, which is the increment of the cable diameter in order to provide the needed strength and avoid failure. One-way cable systems were analysed in Models III and IV.

3.6.2.1. Clamped attachment

The same process as with the previous models was carried out in this case's load appliance, testing it with decreasing wind load values until the bearable amount was reached. The applied wind load was **0.2kPa**.

One-way cable system with clamped attachments was analysed in Model III.

3.6.2.2. Bolted attachment

The one-way cable system with bolted attachments was analysed with an applied wind load of **1kPa**, according to what has been previously explained.

The one-way cable system with bolted attachments was analysed in Model IV.

3.6.3. Variables summary

	Cable diameter (mm)	**Cables Pre-tension** (kN)	**Wind load** (kPa)
Model I	22	50	0.2
Model II	22	50	1
Model III	30	90.5	0.2
Model IV	30	90.5	1

Table 3.4. Models variable parameters

	Cable deflection criterion **De_c** (mm)	**Cable allowable stress** **σ** (MPa)
Models I and II	227.7	567.5
Models III and IV	325.3	567.7

Table 3.5. Models performance criteria

3.7. Results of Nonlinear Analysis

A static analysis of each cable net model was conducted by the nonlinear finite element method to assess whether the whole structure met stability and resistance requirements, and the results obtained are presented in this section.

The analysis provides results on the glazing system behaviour. Maximum tensile stresses were all observed at the corner locations of glass panels for all the models. Special attention was paid to the stress levels observed in the glass panels around the glazing attachment. Glass maximum tensile stresses were acceptable for all the models, being under the stress limit for heat-strengthened glass stated in international glass codes 58MPa.

	Glass max. tensile stress $\sigma_{glass,max}$ (MPa)
Model I	23.46
Model II	16.25
Model III	36.01
Model IV	15.34

Table 3.6. Numerical results of analysis -Glass (Strand7)

Additionally, results showing deformation of the cable net, maximum axial force and stress in the cable net, and maximum reaction at the boundary nodes of the cable net are also provided. These are presented for each model and main results are summarized and commented. Note that figures that display deformed elements have a 5% scale deformation.

	Cable max. deflection $u_{cable,max}$ (mm)	Cable max. axial force $H_{cable,max}$ (kN)	Cable max. axial stress $\sigma_{cable,max}$ (MPa)
Model I	39	57	150
Model II	209	101	267
Model III	66	63	166
Model IV	219	189	267

Table 3.7. Numerical results of analysis - Cable (Strand7)

Maximum deflection of cables in clamped attachment façades are considered very small deflections and show that Models I and III are feasible for the present prototype's dimensions and low wind load.

Larger values of cable deflection were observed for models featuring the bolted attachment (Models II and IV), not only due to the increment of wind load, but also because of the glazing attachment method. The bolted glazing models showed a tolerance for larger deflections due to the type of attachment that allowed more movement overall. Stress values for both cables and glass panels are under allowable limits.

On the other hand, the increased cable diameter in Models III and IV, created a higher strength bearing system in the vertical direction, but the elimination of horizontal cables led to a more flexible system with larger deflections compared to the regular cable net. Model IV showed the largest deflections given the flexibility of the system due to both the one-way cables distribution and the bolted attachment type. As we have already mentioned, this type of attachment allowed for more movement leading to large deflections but lower stress levels related to the previous models.

Additionally to the main results presented, verifications for the cable net performance are given below for each model.

3.7.1. Model I: Two-way cable net with clamped attachment

- Applied wind load: **W = 0.2kPa**

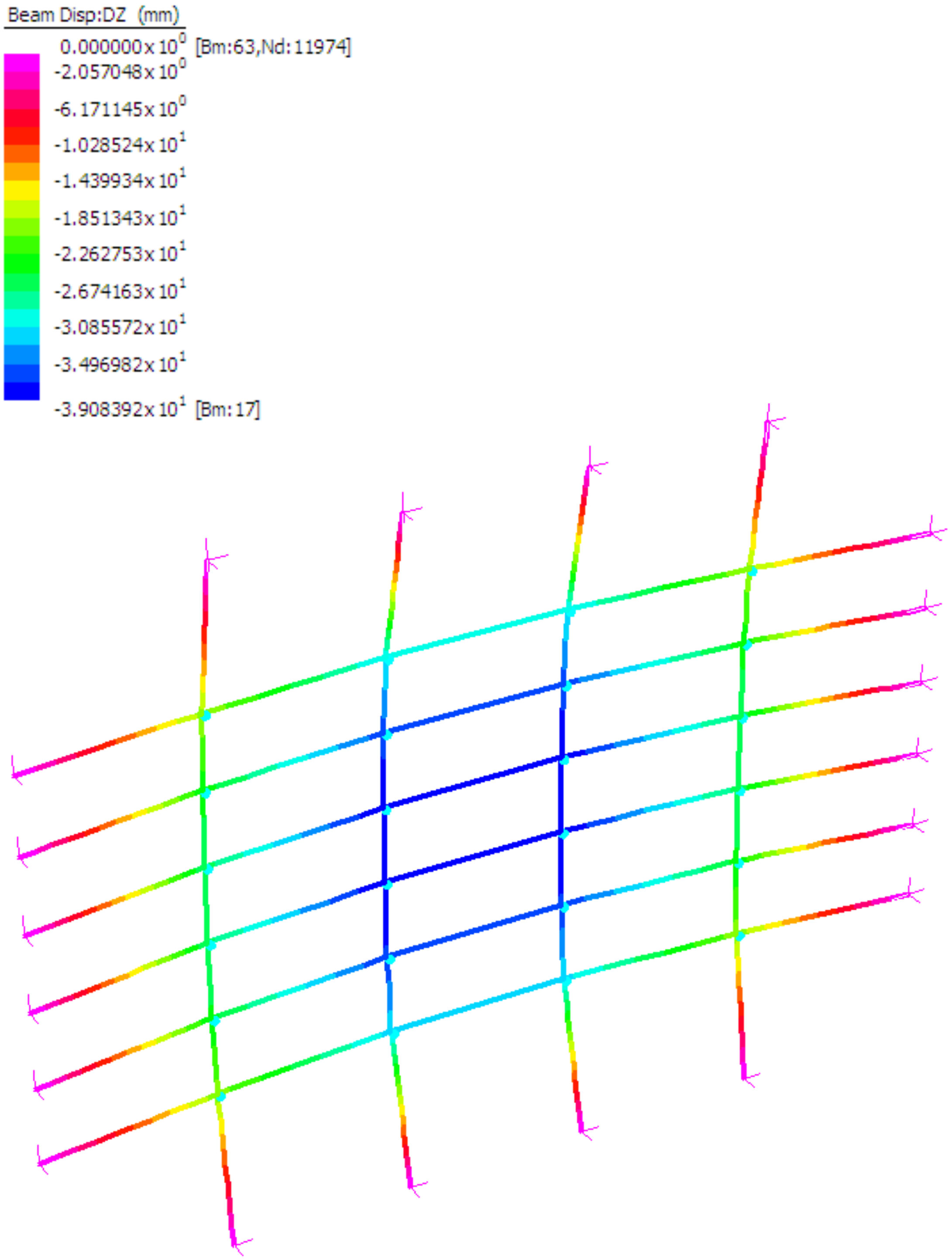


Figure 3.6. Model I. Cable net Deflection (Strand7)

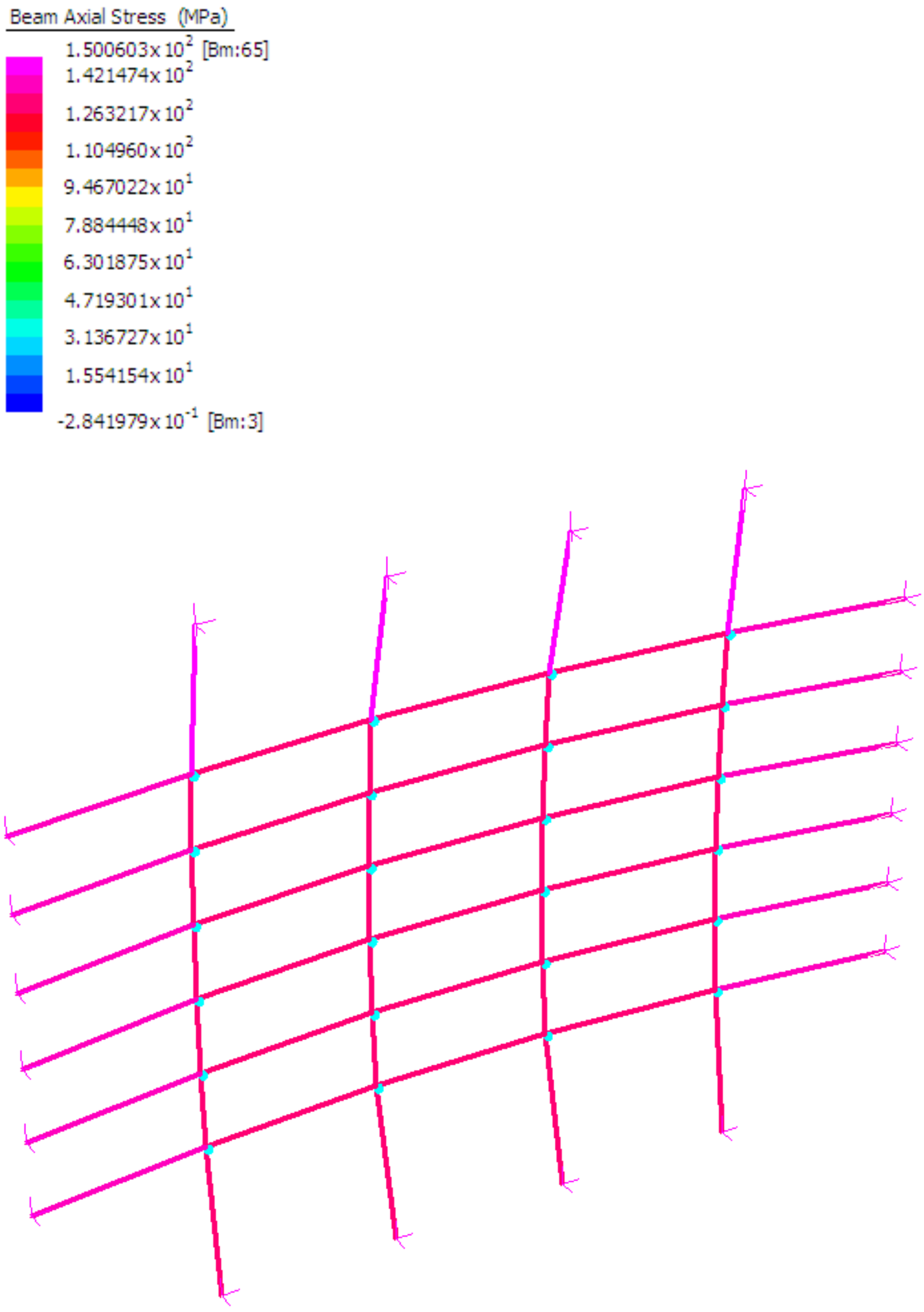


Figure 3.7. Model I. Maximum axial stress in the cable net (Strand7)

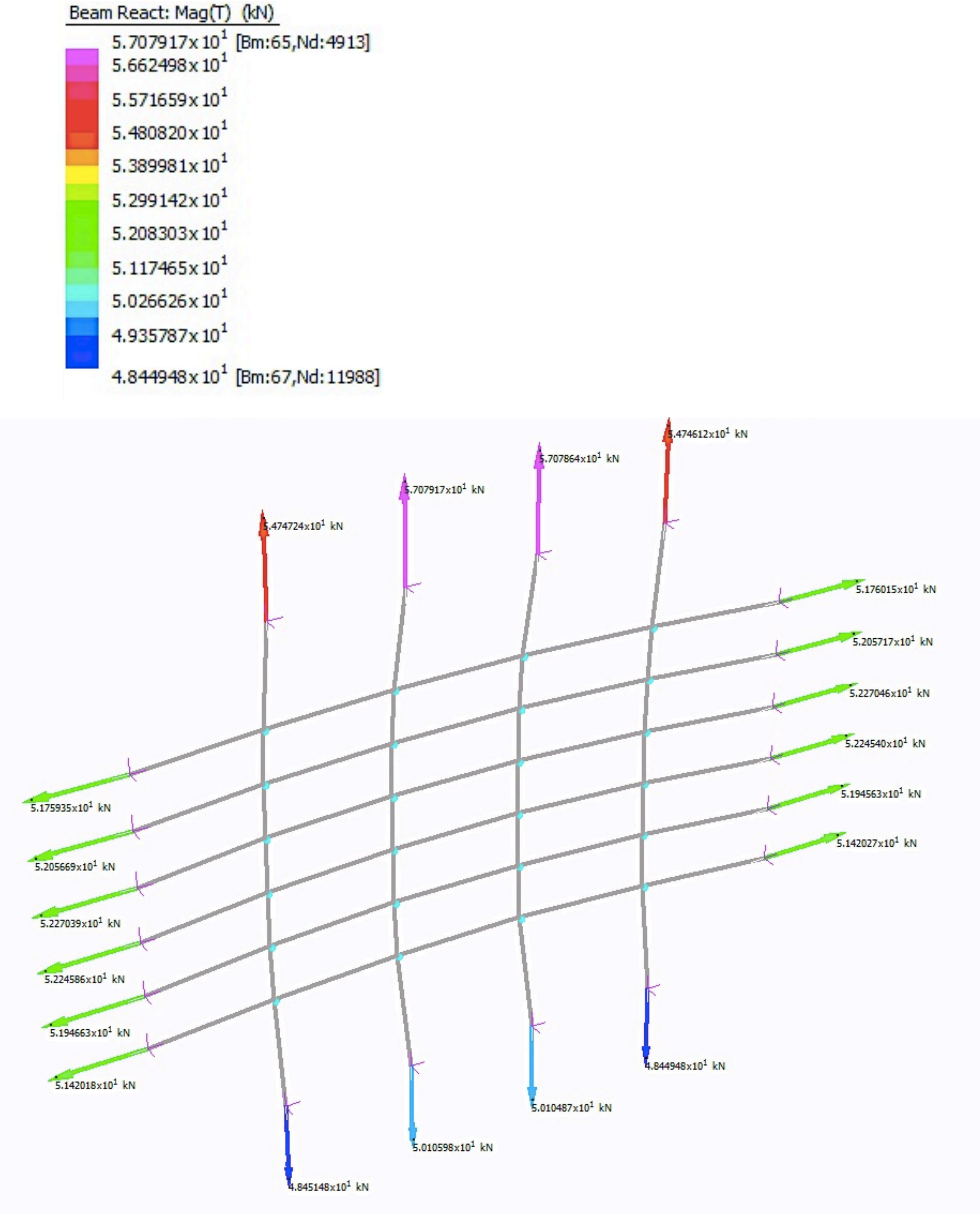


Figure 3.8. Model I. Reactions in the cable net (Strand7)

Maximum displacement of 39mm is observed in the central zone of the cable net. This is a very small deflection and shows that this model is feasible for the present dimensions and low wind load.

$$\frac{39.08\,mm}{De_c} = 0.17 \qquad 0.17 < 1.0 \qquad \checkmark$$

Maximum axial stress levels observed take place at the ends of the cables close to their anchorage connection to the primary structure of the building.

$$\frac{150\,MPa}{\sigma} = 0.26 \qquad 0.26 < 1.0 \qquad \checkmark$$

The cable net works effectively as a tensile structure and the stresses observed are acceptable.

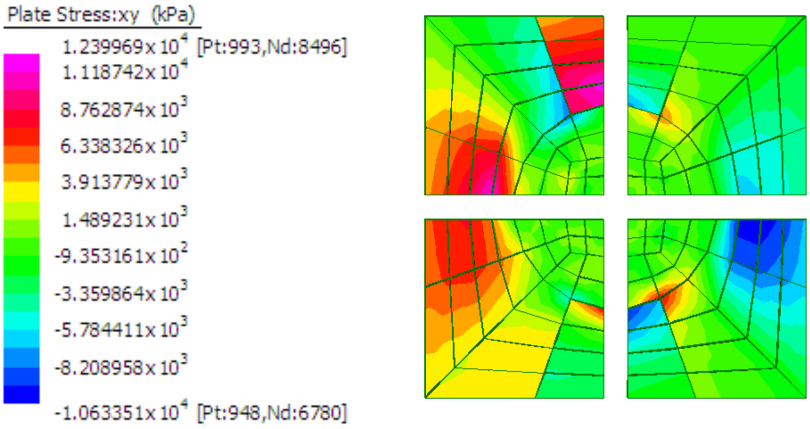


Figure 3.9. Model I. Glass plates stress distribution at the corners around the clamped attachment (Strand7)

Stress values and distribution around the glazing attachment provided the most significant observations. This model features a clamping device previously defined that fixes four glass panels together by clamping their corners, and is connected to the cable supporting system by means of a rigid connector. Maximum tensile stresses were always observed at the corners of the glass panels, and stress peaks at other locations such as the centre of the panel were always lower than the used tensile strength.

3.7.2. Model II: Two-way cable net with bolted attachment

- Applied wind load: **W = 1kPa**
- Cable diameter: **22mm**

$$\frac{209\ mm}{De_c} = 0.91 \qquad 0.91 < 1.0 \qquad \checkmark$$

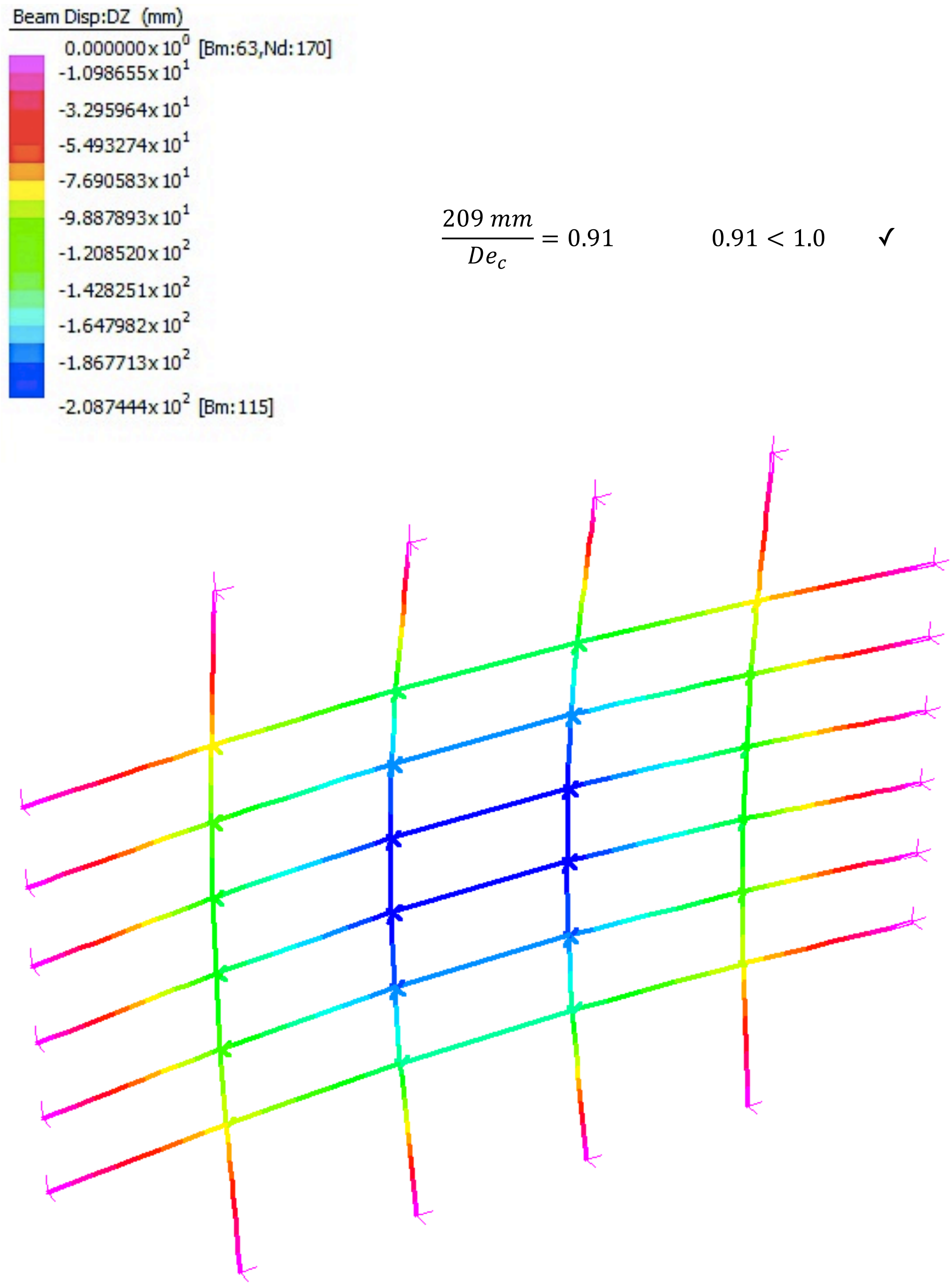


Figure 3.10. Model II. Cable net Deflection (Strand7)

$$\frac{267\ MPa}{\sigma} = 0.47 \qquad 0.47 < 1.0 \quad ✓$$

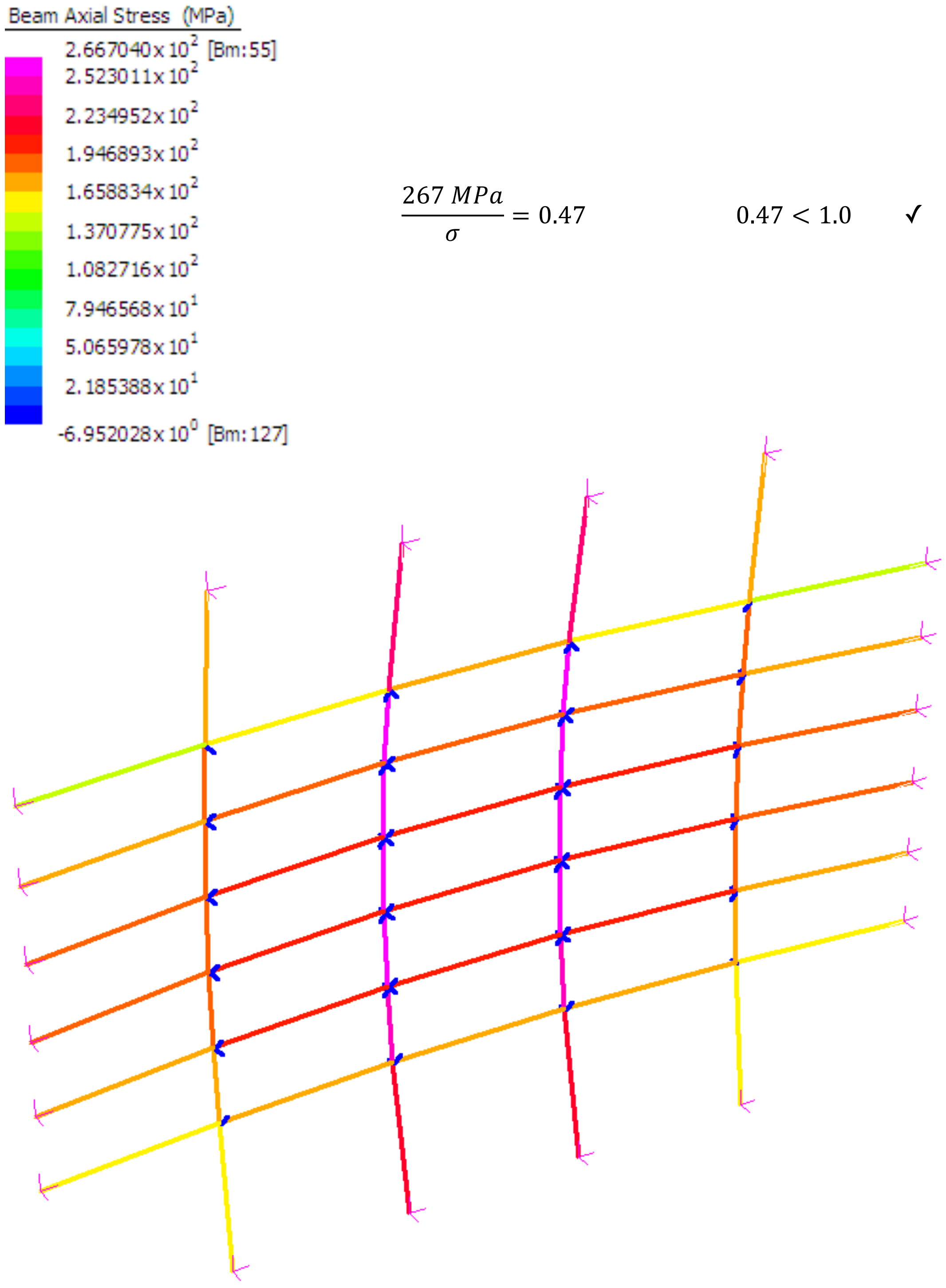


Figure 3.11. Model II. Maximum axial stress in the cable net (Strand7)

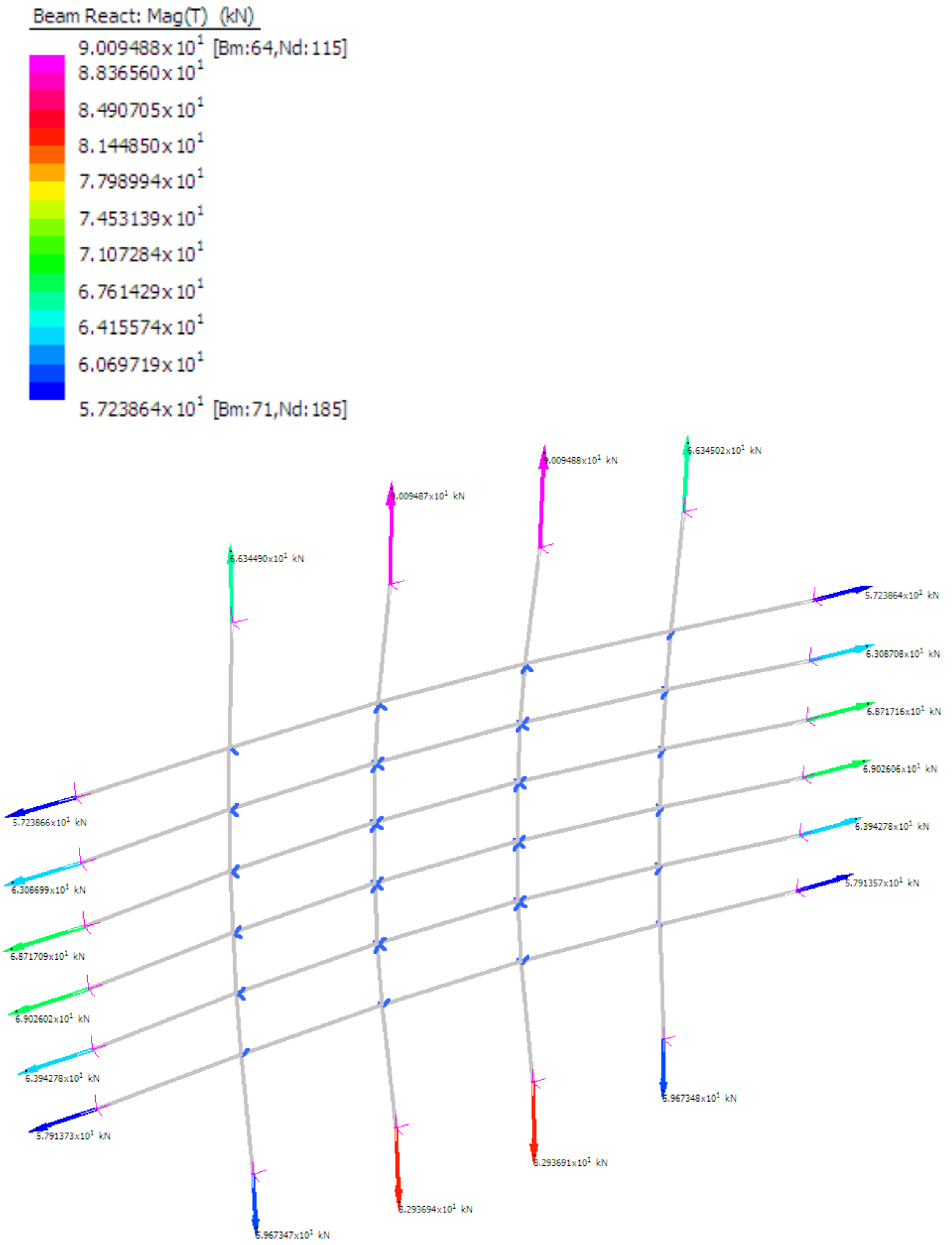


Figure 3.12. Model II. Reactions in the cable net (Strand7)

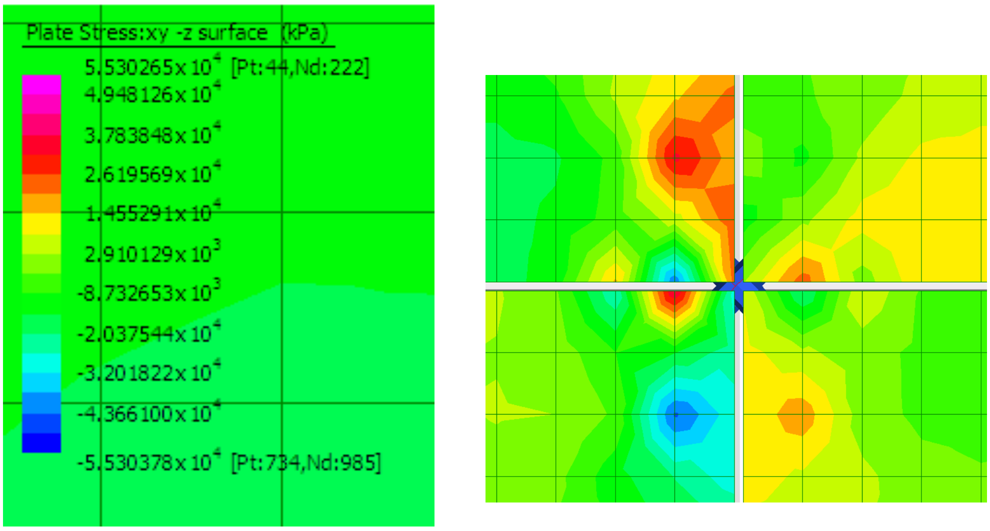


Figure 3.13. Model II. Glass plates stress distribution at the corners around the attachment (Strand7)

Performed simulations showed that maximum stresses occur at the corners of the glass panels. Fracture is prevented by locally toughening the glass at the corners around the drilled holes.

3.7.3. Model III: One-way cable system with clamped attachment

- Applied wind load: **W = 0.2kPa**
- Cable diameter: **30mm**

$$\frac{66\,mm}{De_c} = 0.20 \qquad 0.20 < 1.0 \qquad \checkmark$$

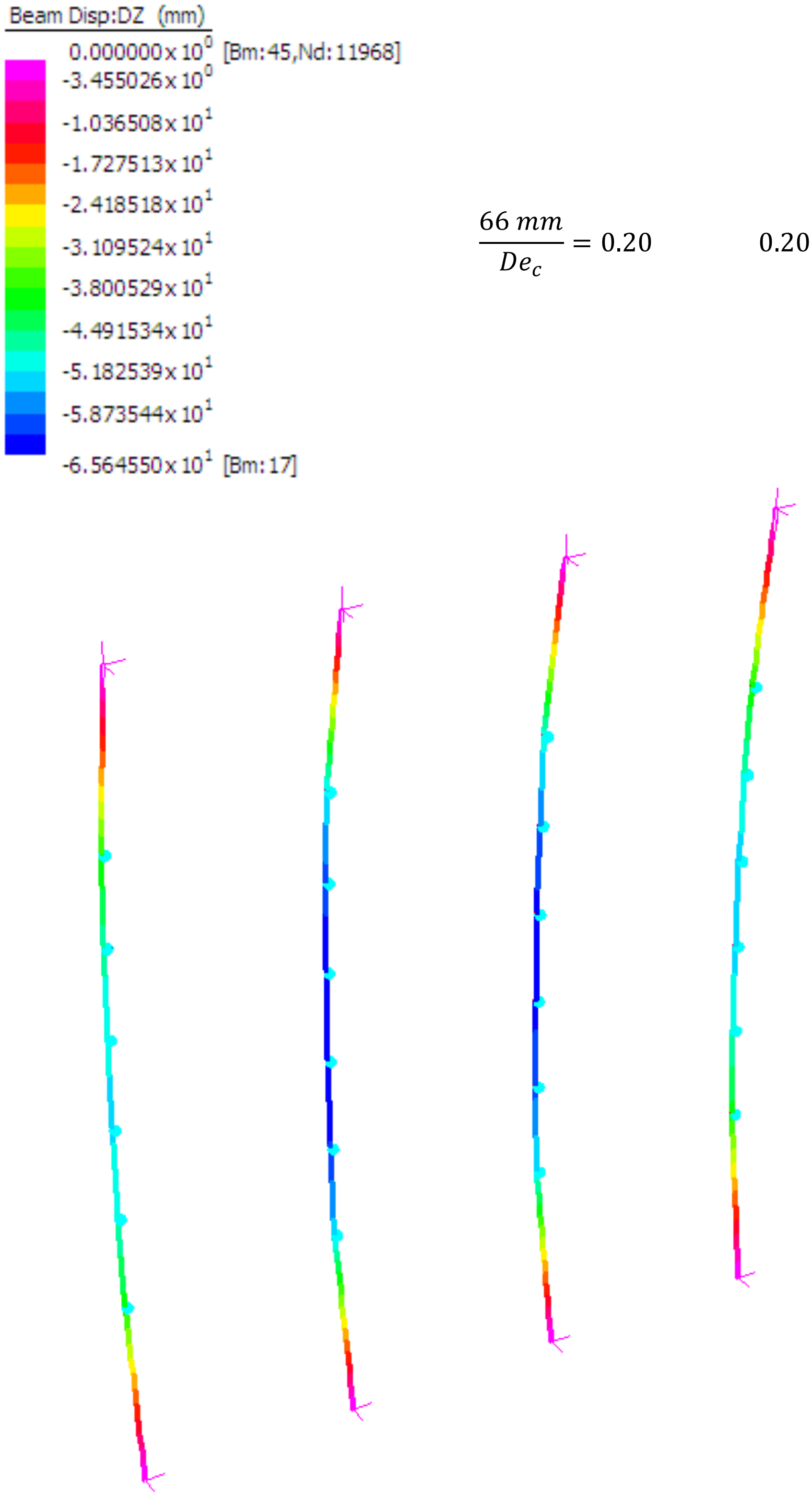


Figure 3.14. Model III. Cable net Deflection (Strand7)

$$\frac{166\ MPa}{\sigma} = 0.29 \qquad 0.29 < 1.0 \quad ✓$$

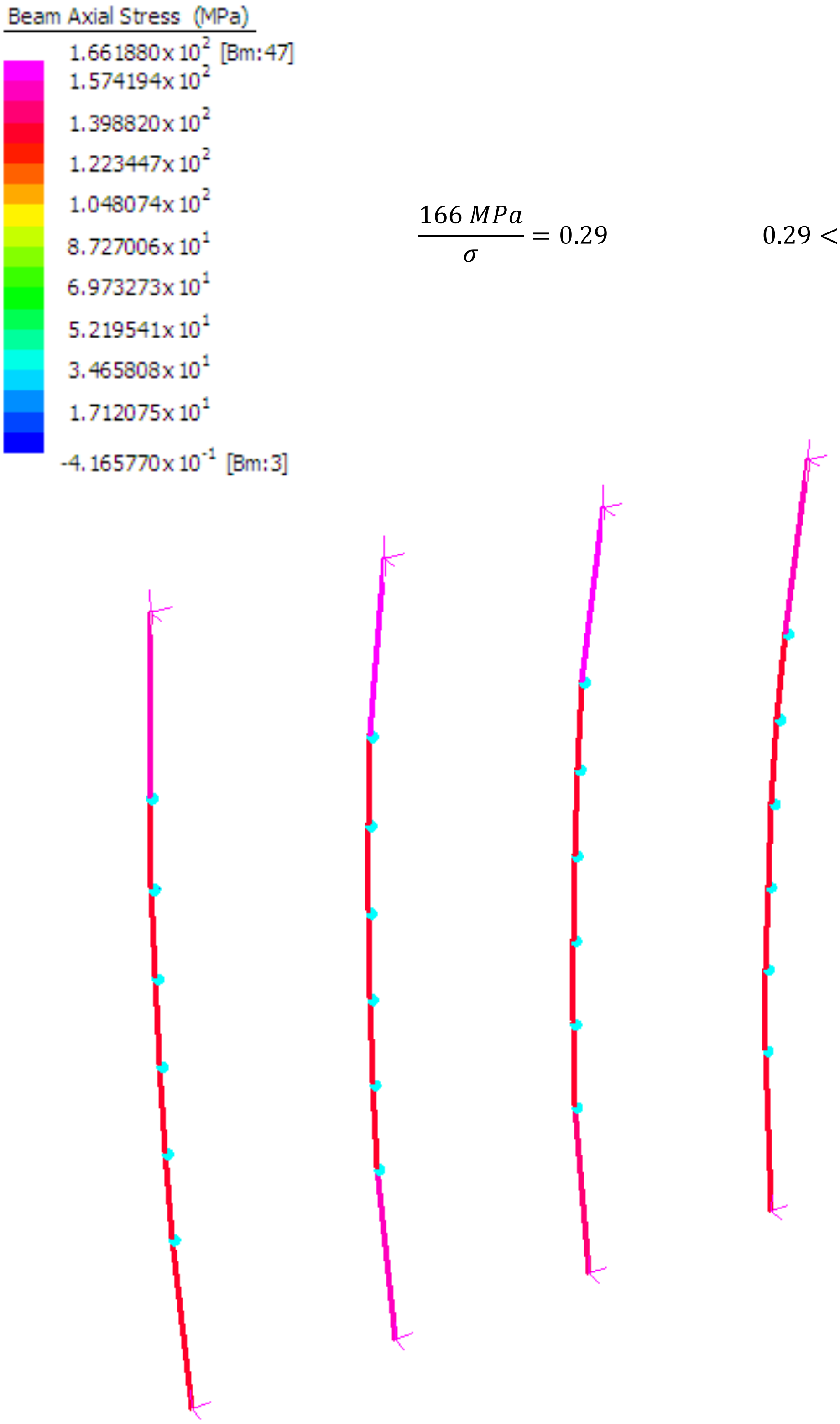


Figure 3.15. Model III. Maximum axial stress in the cable net (Strand7)

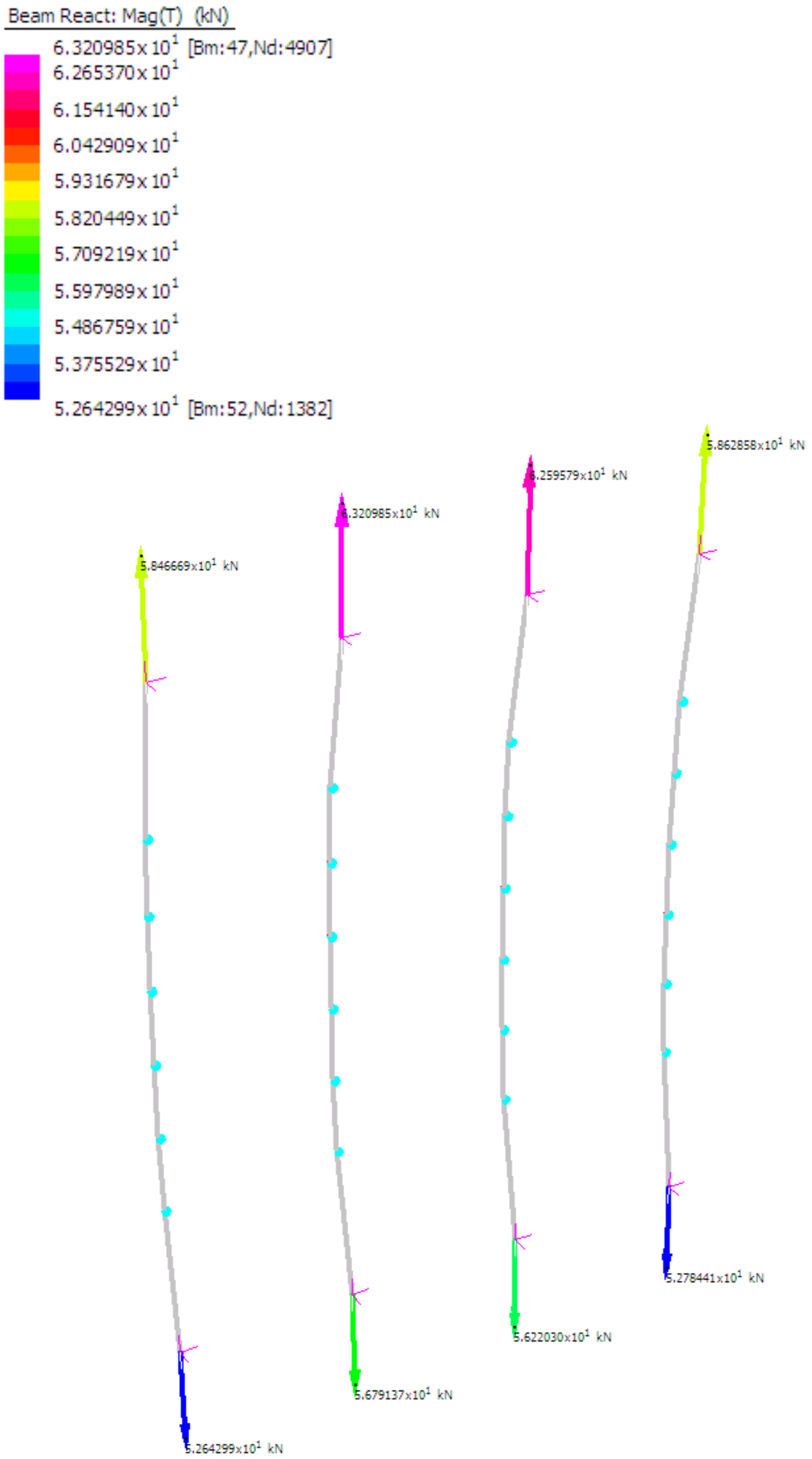


Figure 3.16. Model III. Reactions in the cable net (Strand7)

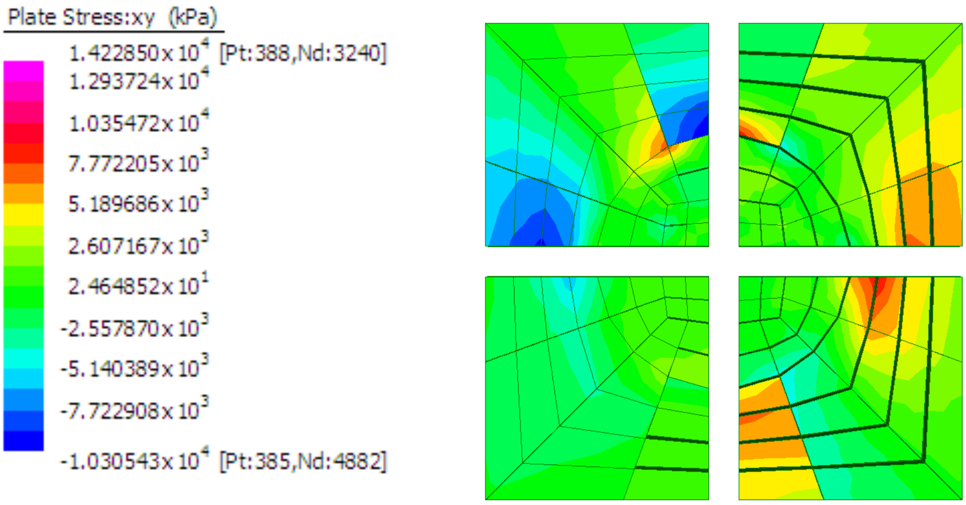


Figure 3.17. Model III. Glass plates stress distribution at the corners around the clamped attachment (Strand7)

3.7.4. Model IV: One-way cable system with bolted attachment

- Applied wind load: **W = 1kPa**
- Cable diameter: **30mm**

$$\frac{219\ mm}{De_c} = 0.67 \qquad 0.67 < 1.0 \qquad \checkmark$$

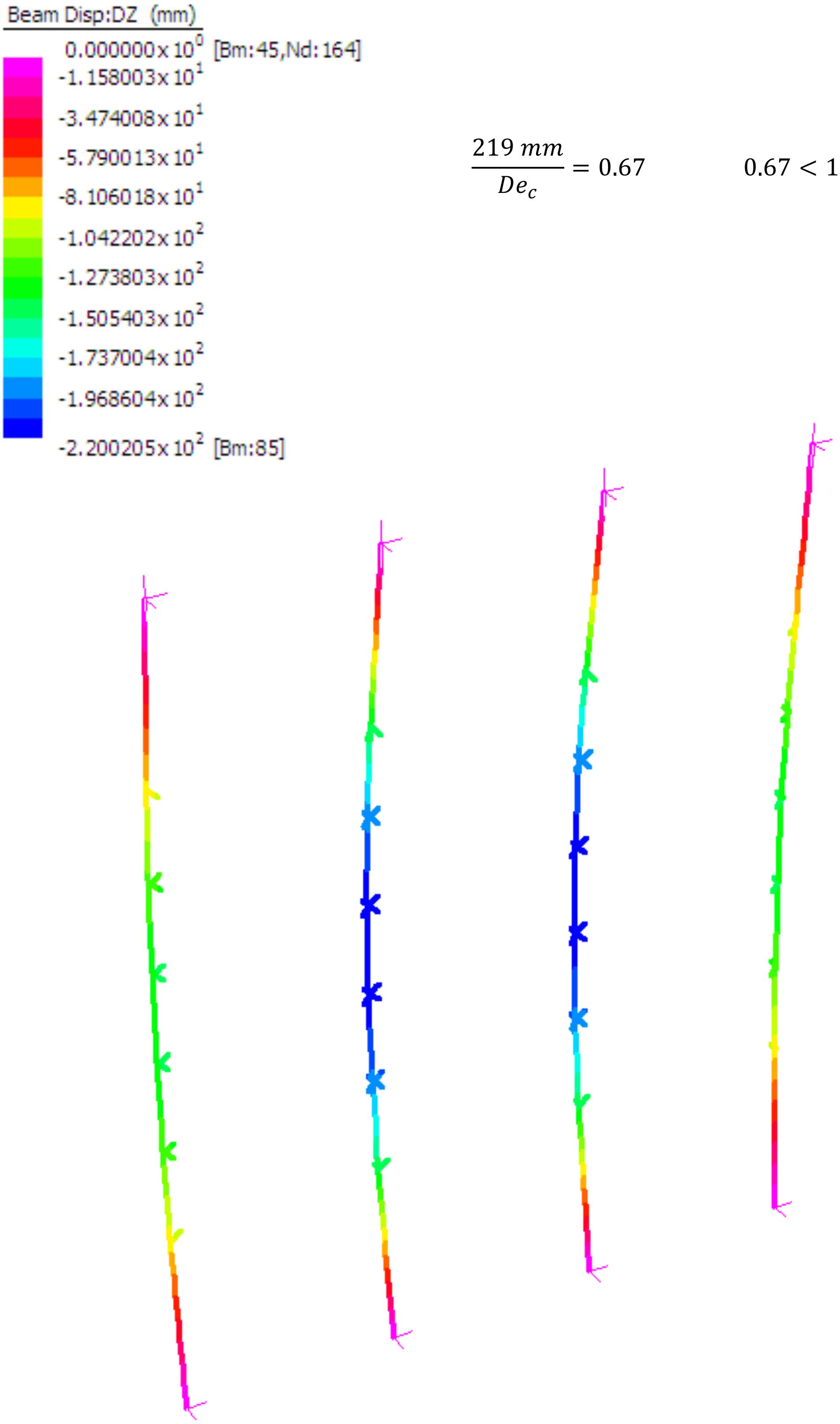


Figure 3.18. Model IV. Cable net Deflection (Strand7)

$$\frac{267\ MPa}{\sigma} = 0.47 \qquad\qquad 0.47 < 1.0 \qquad ✓$$

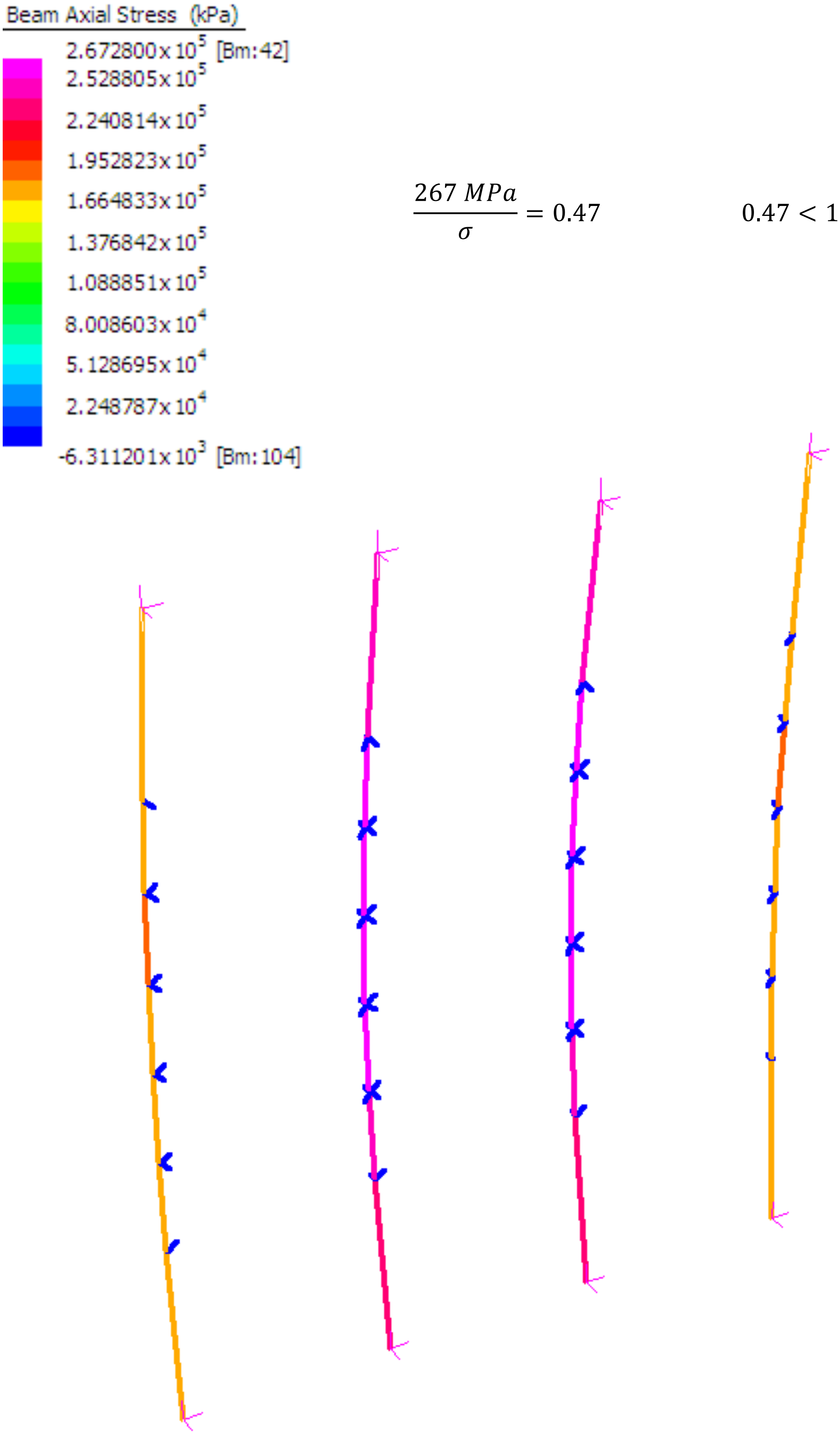


Figure 3.19. Model IV. Maximum axial stress in the cable net (Strand7)

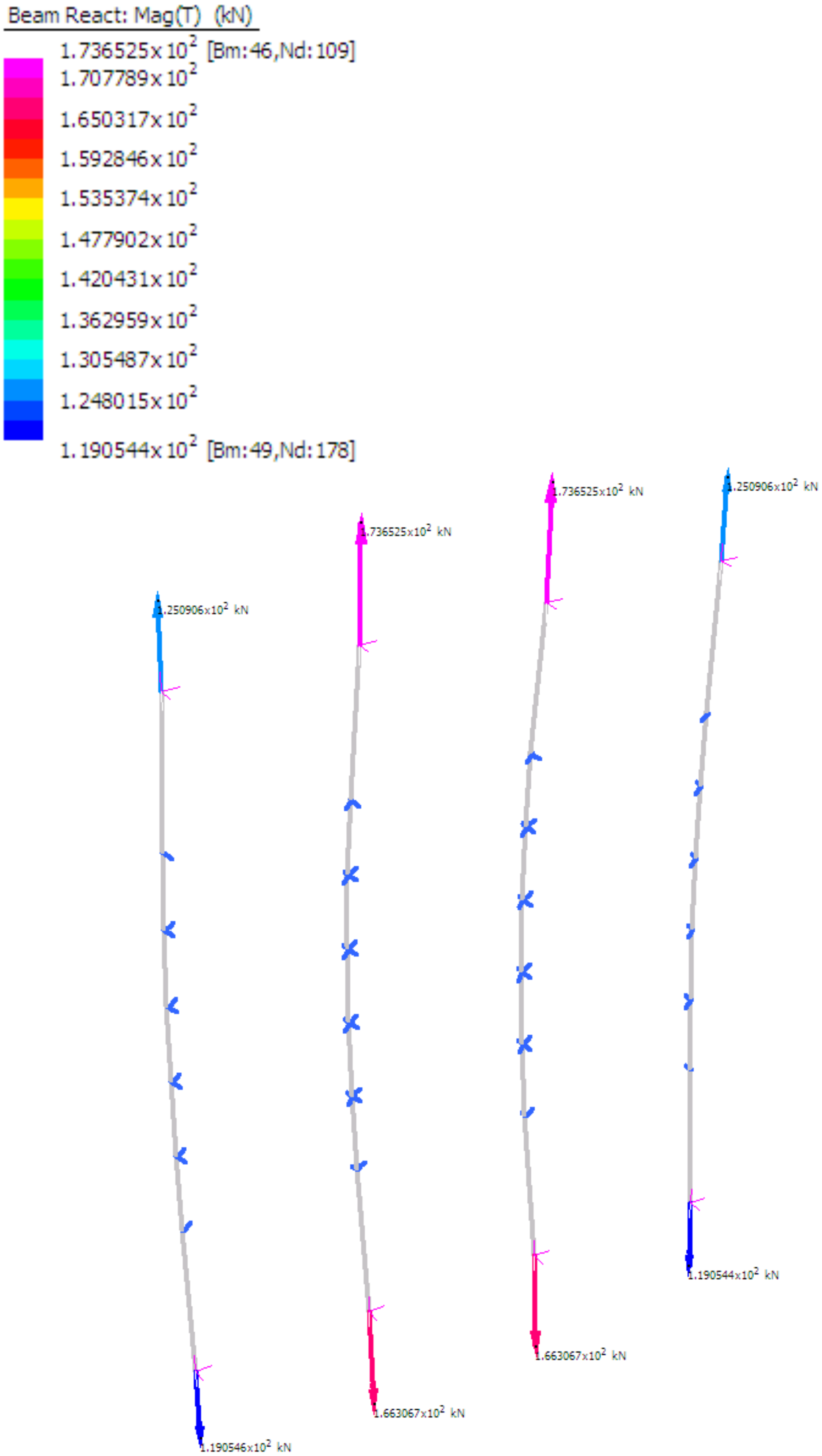


Figure 3.20. Model IV. Reactions in the cable net (Strand7)

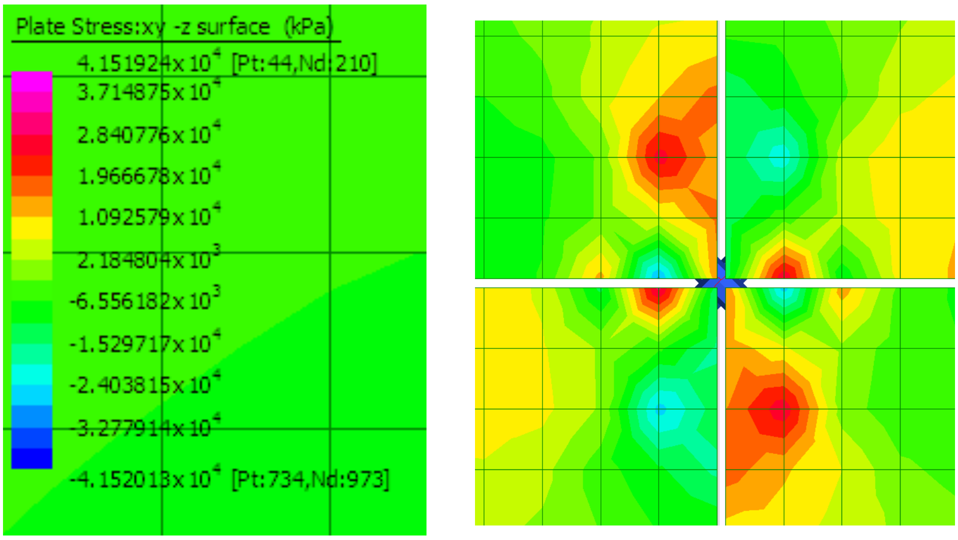


Figure 3.21. Model IV. Glass plates stress distribution at the corners around the attachment (Strand7)

After carrying out the non-linear analysis of the various numerical simulations, the testing process and the final results have shown that bolt-attached glass wall models have lower stiffness and can tolerate large deflections. Because they are only attached by one point in the numerical simulation rather than having the whole corner clamped, they allow more movement leading to large deflections and lower levels of stress. It is important to notice that the holes in the glass have not been modelled, and, instead, one node located at 100mm from both sides of the corner has been considered as the point where the bolt should be drilled. On the other hand, clamp-attached glass wall models have developed larger stresses because movement is more restricted. Overall, considering the dimensions of the current prototype, clamped attachments are not recommended here because they would require thicker glass panes in order to be efficient under higher wind loads.

Regarding the cables distribution and the spanning directions, one-way systems required thicker cable diameters to increase the cables breaking strength and withstand the wind loads without failing. Two-way systems have been proved to work efficiently as a structural supporting system.

Under uniform wind load, the cables movement is symmetrical about the mid-span, and maximum displacements are observed at the centre of the wall. Maximum stresses in the pre-tensioned cables are controlled under allowable stress values, and these are transmitted to the primary building structure entailing reactions at the anchorages that must be borne and considered in the building's structural design.

The deflection of the glazing panels caused rotation about the attachments and this had to be resisted, therefore developing stresses within the capacity of the glazing material. Higher wind loads of 3kPa and 2kPa were tested initially applying them to the numerical models, but the systems were observed to fail unable to withstand the rotation and stresses developed around the attachments.

Chapter 4. Conclusions and Recommendations

The objective of this thesis was to test the cable supported glass façade system in various configurations and to draw a set of conclusions regarding the use of the aforesaid based on its mechanical behaviour.

After carrying out the analysis of the different numerical models, and by means of a trial and error process, the findings and deductions obtained are exposed hereunder.

4.1. Glazing attachment systems

One of the most relevant findings in this study is related to the influence of the type of glazing attachment on the system. It has been observed that the type of glazing attachment affects heavily on the wind load that the system is able to bear.

For models featuring the clamped attachment, which sets all adjacent glass corners into a vertex clamping component fixed to the cable net structure, the current prototype was only able to withstand wind loads of up to 0.2kPa, which is considered to be a rather low load and it is not suitable for real cases considerations, being 1kPa an appropriate reference. Therefore, despite being very advantageous in terms of avoidance of glass drilling and tolerance of suppliance and installation requirements, the use of clamping devices for glazing attachment needs to be restricted depending on geometrical parameters such as the dimensions and thickness of the glass panels.

The supporting method, by means of neoprene pads on both faces of the clamp, works with friction against the glass supporting the dead load of the panels. Considering the size of the glass panels as a fixed variable in this study, they produce a heavy load given their big dimensions (3mx1.25m), which together with a high wind load, makes the system fail because the clamping device is not able to support the glass panels.

Moreover, maximum stresses for clamp-attachment models observed at the edges of the glass panels around the clamping areas, provided values much higher compared to bolt-attachment models, regardless of the lower wind load applied. The movement restriction that provides the clamping system developed higher stresses in the glass panels making them more prone to break.

In case the use of a point-fixed clamped system was required, it would be necessary to increase the thickness of the glass panels which currently is set to 15mm.

On the other hand, bolted attachments, consisting of connecting the attachment device to the glass panels by drilling metal bolts at the corners of the panels, has proven to be suitable for the current prototype being able to withstand wind loads of up to 1kPa without causing failure or breakage. Deflections and stresses are controlled under required limits and the structural glass façade's components behave successfully under applied loads. However, the point-fixed bolted system requires the consideration of a set of important issues.

In the first place, a requirement regarding the type of glass arises. Toughened glass is required in bolted-attachment systems to accommodate the stress concentration resulting from drilling and bolting directly to glass plates. The dead weight of the glass is supported by the fittings and bears directly on the bolts, therefore it is necessary to maximize the strength of the glass around the joints. The glass is first drilled with a diamond drill forming the bolt holes, and then it is submitted to the process of toughening. The glass can also be submitted to an additional treatment, called heat-soak treatment, as a quality check to reduce the risk of spontaneous breakage due to inclusions in the glass panels. In this process, the glass undergoes a special heating cycle that causes the glasses containing inclusions or impurities to break prematurely. Both toughening and heat-soak treatments must be done after the glass has been cut, drilled and processed.

Another important matter are the bolt holes. Stresses develop due to movement restriction, therefore provision is usually made for bolted fixings to move freely in-plane relative to the support attachments to avoid generating any additional stresses. The holes in the attachments are typically either oversized to allow movement in two directions, or slotted horizontally to allow horizontal movement but still support the glass weight. Two typical arrangements are shown in figure 4.1. Glass panels in drilled systems are most typically hung from the top connections and allowed movement at the bottom, while clamped systems support the dead load at the bottom of the glass panels and movement is provided at the top. The size of the holes and slots in the attachments is decided depending on the amount of adjustment that is needed to accommodate tolerances and on the allowances needed for movement due to thermal effects.

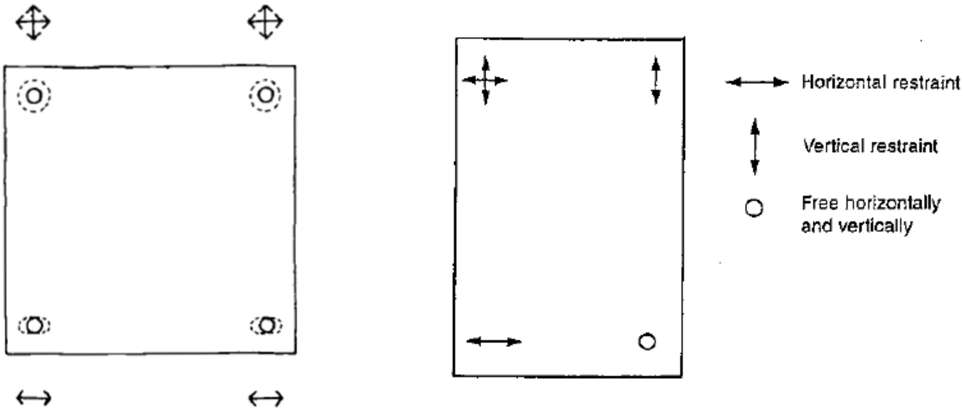


Figure 4.1. Allowance of movement in bolted glazing attachments

The requirement of drilling the glass panes, together with the necessity of insertion of a sealing ring around the bolt hole to maintain a hermetic seal in laminated glass units, affects on the cost of the system by increasing it. However, the alternative clamping strategy, which eliminates the necessity of perforating the glass, also presents other cost considerations such as the ones concerning the clamping hardware, which is more complex and costly than in bolted systems.

Summing up, the present prototype, which features big size glazing panels that entails heavy dead loads, is suitable for bolted glazing attachment systems under wind loads; but further assessments would need to be done regarding the bolt holes provision.

4.2. Cable supporting systems

Regarding the cables arrangement, it has been proved that one-way vertical systems are suitable for prototypes such as the present one, with wider span in the horizontal direction and relatively short vertical span where the addition of horizontal cables does not add significantly to the stiffness of the wall, i.e. shorter but wide walls typically covering heights of one story, but as long as ensuring appropriate cable diameters that provide the sufficient strength. High pre-tension loads require more substantial cables as discussed, and also stronger connections and stronger supporting structures overall. It is always therefore desirable to design a cable net structure that satisfies all displacement and stress performance criteria with as small a level of pre-tensioning as possible.

Nevertheless, two-way systems still allow for longer spans to be constructed and they also allow for simpler detailing at boundary conditions connecting to the building's primary structure as the deflection of the cable net is always zero at the perimeter. The broader applicable scope of the two-way cable net technology includes entire atriums, large entrance lobbies, translucent roof supporting structures, and so on, and they are widely used in airport terminals, hotel halls, exhibition centres, among others.

4.3. Future research

Selection, design and application of cable supported glass façade technologies are complex processes that require the consideration of critical structural issues including the behaviour of the overall structure, the behaviour of each component of the system, but also the behaviour of the structure after the failure of one or more glass elements, and the safety implications of failure of a piece of glass involving issues as the likelihood of people being injured by falling glass. This is only an example of the wide scope that the cable supported glass façade technologies cover.

Several research studies have been carried out in topics more or less related to the presented technology. Evaluations of deformation and stress of glass panels supported by specific joints, static experiments determining load-carrying capacity of armored glass panels, studies on the factors that affect this load-carrying capacity of the glass panel with a specific type of joint, investigations on static and dynamic performance of cable net facades as a function of glass panel stiffness, and so on, are only a few examples of interesting contributions to the glass façade technologies. However, the complicated stress state of glass panels is, for instance, a topic to be much further developed in cable net facades. Furthermore, a limited amount of research has been conducted on the warping distortion of glass panels in a cable net facade, making it an interesting topic of study to research on. On another theme, focusing on breakage patterns of glass panels in cable net façades is also an interesting research work, to study the spontaneous breakage of glasses like tempered glass and their developed butterfly pattern, as well as analyzing relations such as the one between inclusions dimensions found in the breakage origin and the later breakage of the glass panels.

The cable supported glass façade technology is a topic in continuous evolution and still subject of study in many different fields willing to become more and more efficient, accessible and economical. And this study serves as a contribution to the development of this technology and encourages the continued development of such an interesting specialty.

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