Spider web design

"Research and development on the application of spider silk and web typology in the building industry"

Master's research

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Preface

This report is the documented result of the work carried out as a graduate Master's thesis at the University of Delft at the faculty of civil engineering and geoscience.

"Spider web design" as topic was very challenging for me, since it was, first of all, a new innovative idea but also a combined design-modeling pro¬-ject.

Moreover, I found Biomimicry as a design strategy for a façade fascinating and a chance to look in a different way the regular designing process.

Blast as the main design loading was new to me. Although I could immediately recall images about the effects of explosions on structures from movies or the news (a shattered hotel, a damaged police post, a domestic gas explosion, the explosive failure of an aircraft pressure bulk¬head or of a jet engine), I never had any relevant course in my long studying career as a civil engineer.

As it is always the case for the design of innovative projects, a lot of difficulties occurred since there were no references to similar building structures. However, all throughout the process of my research I had the great privilege to be surrounded by people, who constantly encouraged me on different levels, be it academic or moral. To all of them I would like to give my honest thanks.

I would like also to express my sincerest gratitude to my mentors Prof.ir. R. Nijsse , Dipl.-Ing. T. Klein and ir. P. Eigenraam , who enriched this thesis with their different expertise, as well as to dr.ir. F.A. Veer for his guidance and his instructive comments. Furthermore I would like to thank Phaedra Oikonomopoulou , who although not being part of my committee, took the time to consult me regarding the connection related issues.

Finally, special thanks go to my good friend and colleague Dion Jansen; It wouldn't have been possible for this thesis to be realized without his valuable contribution.

The graduation committee consisted of the following members:

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I. Introduction

This Chapter deals with the motivation aspects of this thesis and namely: the need of blast design nowadays in the building industry, the poor performance of the existing façades against blast loading and finally the biomimicry as a design strategy.

1. Blast design in building industry

It is very often that one can see in the television screen the effects of explosions on structures. A shattered hotel, a damaged police post, a domestic gas explosion, the explosive failure of an aircraft pressure bulkhead or of a jet engine. In spite of this, engineers seem not to be well versed to the design of structures to withstand explosions. This is partly because in the past specifications have rarely included explosive loading as a factor in design and partly because the various dynamic effects of explosions on structures have only been examined as research subjects in a small number of research laboratories(Bulson 1997).

Until the 1960's blast design was reserved for facilities where accidental or chemical explosions could occur. Blast design was not considered for ordinary structures. In the 1960's, though, design guides for blast started to emerge, mostly for buildings with the potential for chemical explosions. In today's world, terrorism is an unfortunate reality and one can sense a change and a growing need for information. Designing for the safety of the occupants in high risk structures has become more important.

The civil blast threat depends critically on geographical location and also on the specific political circumstances of the moment. Since 9-11, blast design has become a well-sought after design not only for federal and military building, but other high risk buildings such as hospitals, banks and international business buildings being a life safety issue (Dick 2012).

2. Facade technologies

Cable net façades are being used worldwide because of their high transparency and geometric flexibility. They have aesthetic advantages and are very common in big buildings around the world for the last twenty years.

Cable net façades consist of three key components: pre-tensioned cables, connection joints and glass panels. The glass panels are connected to the joints through their corners. The cables are also joined together at the joints. The weight of the dead weight of the glass panels and the wind loading on the glass panels are first transferred to the joints. Then, the loading is transferred to the pretensioned cables, which transfer it to the foundations or other supporting structures (Feng et al. 2008).

Figure 1. The facade of the Airport Hotel Kempinski at Munich Airport . With this cable net facade an entirely new structural system was developed for the 25 × 40 m large glazed surface (Schleich Bergermann und partner 2013)

In the literature, there is very limited research on the performance of cable net façades against special loading and specifically against blast and seismic loads. These light and flexible systems are usually not designed to withstand strong blast loads. However, the cable net façades are usually placed at the podium or at the entry levels of a building. As these areas are commonly located at or near the base of a building they are most exposed to blast threats. In addition to that, they are usually used for buildings that host a great number of people at the same time (such as airports, hotels, music halls, libraries etc) and consequently are more vulnerable to terrorist attacks (Wellershoff 2011).

According to the International Organization for Standardization they should offer protection against weak blast loads. However because of the flexible behavior and low specific mass, the structural response of the blast loaded cable net facade is quite different in comparison with the structural response of more massive and rigid protective components made of steel or reinforced concrete (Fu 2012).

This poor performance against blast loading is lately becoming an important issue in the design of cable net façades. The need for improvement is obvious, as it is not easy to design the glass panels to have a flexible behaviour, similar to the one of the cable structures. For this reason it is useful to explore possibilities in this direction. This can be done by using nature as inspiration and by trying to understand and "copy" the way natural structures respond to similar challenges. The next paragraph deals with Biomimicry and introduces a biomimetic approach to the problem described above, specifically using the analogy of spider webs and cable net structures.

3. Biomimicry as design strategy

This chapter introduces the characteristics of Biomimicry, as it constitutes the motivation and the source of inspiration of this study. The term biomimicry or biomimetics come from the Greek words bios (βίος), meaning life, and mimesis (μίμηση), meaning to imitate. As the etymology of the word describes biomimicry is the imitation of the models, systems and elements of nature for the purpose of solving complex human problems (Wikipedia 2013b).

Biomimetics as an idea is not new. Nature always was a source of inspiration not only for artists but also for engineers. The famous Catalan architect Gaudi had trust in the beautiful efficiency of natural engineering. He had understood that nature is constructed by laws of mathematics. His"tree-inspired" columns that use hyperbolic paraboloids as its base, catenary arches, spiral stairways and conoid-shaped roofs make him undoubtedly the predecessor of the modern science of biomimetics.

However Biomimicry is more than just inspiration from the nature; it's a methodology that's being used by some of the biggest companies and innovative universities in the world. The natural world provides an immense database of designs that can inspire creative thoughts.

But can nature do a better job than engineers?

Nature has its own principles evolving a set of strategies that have sustained over 3.8 billion years. It integrates and optimizes these strategies to create conditions conducive to life (Bhushan 2009).

Many examples can be given of optimal structures in nature, since nature has its own optimising law, the Darwinian law of survival of the fittest (Darwin 1859) and evolution resulting from it. For many "structures" in nature, gravity is an important load and the structures are optimised accordingly.

Although scientists have made big achievements, our solutions cannot still compete with the solutions nature found in the struggle to survive. For example, many of the most advanced robots in use today are still far less sophisticated than ants that "self-organize" to build an ant hill, or termites that work together to build impressive, massive mounds in Africa. (Wyss Institute 2013).

Sir D'Arcy Thompson in his work 'On Growth and Form' explains the analogy between nature and structural design of many natural structures. For instance, the book discusses the spider webs and their principles of surface tension. The same book deals as well with the similarities between spider webs and cable structures (Figure 2 and Figure 2).

The threads produced by the spider are pure tension elements. The web is fixed at its boundaries, where the tension forces from the web form equilibrium with the support forces. The web is loaded by its own weight, dew drops, wind loads and the impact of a prey. Extensive information about the spider webs and their structural properties are discussed in the next chapter.

Figure 2. Patterns from Nature were utilized in many of Gaudi's designs. Here, in the Sagrada Familia's spiral staircase the form influence from the Nautilus Shell is clear. (ThisBigCity 2013)

Nowadays the development of technology offers the means to investigate in a micro level any leaving creature and also provides us the capacity to mimic nature like never before, allowing the design and fabrication of various materials and devices of commercial interest by engineers, material scientists and chemists.

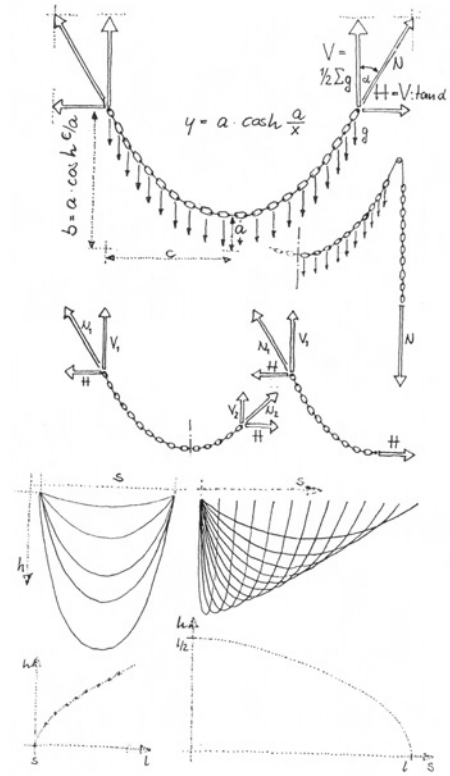

Figure 3. Basic geometry of catenary curves
(Bach 1973)

Figure 4. Spider web and structures based on webs.
(Bach 1975)

4. Case study: Markthal Rotterdam

Markthal Rotterdam is an architectonic residential and market hall project realised in the city of Rotterdam in the Netherlands. Its combination of apartments inside the roof structure and the country's first indoor market is unique for Europe. The structure is realised inside a busy city area, next to the Rotterdam Blaak train, tram and metro station.

Figure 5. Artists impression of the Markthal building and the current facade concept

The two large cable-net façades and the structure's iconic shape create the conditions for its recognition as a city-landmark. The transparent "tennis-like" cable-net façades have of course to deal with many challenges. The big horizontal deflections due to extreme wind loads was one of those demanding challenges, taking also into account the large scale of the façade. The details of the cable-net façades can be found in the fact sheet from Octatube, the engineering company behind the project, in the following pages.

The structure makes an appropriate candidate for a case study when researching blast load design. It is a good candidate because of both the building's importance and position, but also the complexity of the structure and the innovative, large-scale façade design. In detail these are the reasons why Markthal is appropriate as a blast load re-design case-study:

1. Nature of building - public building with open access to everyone.

2. Function of building - thousands of visitors seven days a week plus the apartment residents.

3. Symbolic importance - it establishes a landmark for the city.

4. Location - in the heart of the city, easily accessible area with many customers and residents.

5. Geometry - its large scale and façades.

It should be noted that it is uncommon to propose a re-design concept for a structure that is not even completed (expected delivery October 2014). Usually such re-design proposals are realised for older structures which maybe face new challenges. In the case of the Markthal, this proposal is relevant and useful for two reasons. Firstly, because of the importance of the structure due to its complex design of large scale cable-net façades and its unique for Europe combination of market hall and residential functions. Secondly, because of the increasing awareness of the need to create blast-resistant buildings in order to be prepared against such malicious acts.

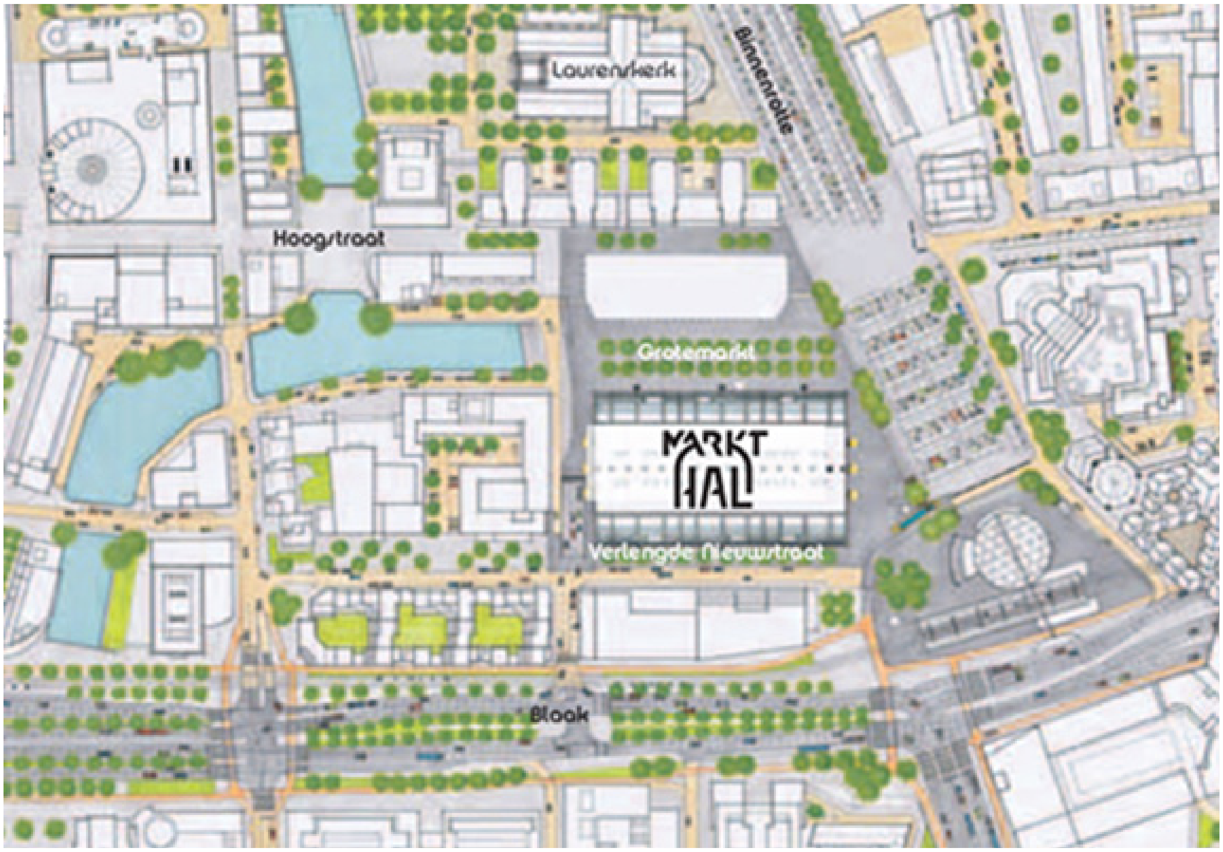

Figure 6. Situation of the Markthal building

Markthal - Factsheet Octatube

Name: Markthal
Architect: MVRDV
Client: JP van Eesteren
Location: Rotterdam
Delivery: 2014 (expected)

General
2 facades
Area per facade: 1258 m2
Height: 35 meters
Width: 42 meters
Openings: 2x3 openings (tourniquettes)

Glass
Dimensions: 1485x1485 mm
Laminated glass 6.6.2 half-hardened, white float glass
Joints: 16 +/- 2 mm, black silicon

Cables
26 vertical cables and 22 horizontal cables per facade
Vertical cables 100 mm behind the joints of the glass panels
Horizontal cables 150 mm behind the joints of the glass panels
Material: galvanised steel strands
Cross section: ø31,3 mm
Characteristic break strength: 884 KN
E-module: 160.000 N/mm2
Maximum transfer force per cable: 513 KN in ultimate limit state
Maximum transfer force per cable: 366 KN in serviceability limit state

Edge Connection
Through "nest-cases" anchored in the concrete
Head plate of 60 mm thick steel, with holes for cable connection and securing materials
Integrated ball joint/hinge (prevents material fatigue for steel cables)
Portals moving together with the facade

“BIGGEST CABLE-NET FACADES OF EUROPE”

Pre-stress and deformations :
250 - 300 KN per cable, of which 50 KN "over-stress" (taking into account loss of pre-stress force)
Elongation from pre-stress 94-147 mm
Theoretical deflection of 70 centimeters (elongation in cable 37 mm)
Rotation along the edge: 1,9-5,4 grad
Rotation in the field: 0,4 grad
Self-frequency facade: 1,4 Hz

Structurally designed for the following loads :
storms (wind power 12)
cable fracture
collision with truck
fire

Partners

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2511 AA Den Haag
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1000 AZ Amsterdam
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www.inbo.com

5. Scope of the work / Main points of focus

In this thesis a new glazing cable net facade is proposed in order to ensure the protection of the Market Hall in Rotterdam in case of an explosion in a near distance of the building, and at the same time, being aesthetically appealing, while following biomimetic principles regarding the conceptual architectural and structural design.

In particular, the success of the proposed system lies in tackling with the three following, strongly interconnected, issues.

First, since this system is a redesign of an existing cable net façade it is obvious that the design should be equally aesthetically appealing. This makes it very challenging as blast resistant building design methods usually conflict with aesthetic concerns, in a sense that their outcome would be a rigid façade with small windows. The motive of this research is to suggest a solution to this problem providing a blast resisting structure but at the same time minimal according to the architectural trend of the times.

Second, human safety should be provided and therefore, avoidance of injury or loss of life will be the primary considerations. It must be ensured that the façade will not only be able to survive a blast explosion but also protect humans behind it. Therefore, a flexible structural system should be developed able of undergoing higher deflections without generating damage. Moreover, energy absorption systems should be integrated on the façade system and ensure the achievement of this goal. As far as injury to occupants is concerned, the main threat is flying glass due to broken glass panes. Since, glass is a restriction for the cladding material it becomes clear that a separate mechanism should developed to secure the endurance of the glass panes during the explosion.

Last, it is required the integration of the above key technological parameters to an overall efficient concept design, with emphasis on the design of the connection system, in a way that high deformations can be permitted in every connection, while at the same time the glass panes should remain connected in the course of blast phenomenon.

The overall design takes advantage of the "biomimetic" principles of spider webs (as they constitute an ideal example of lightweight structures with excellent performance against impact loading) and envisions cable net façades as glass armours for future buildings.

6. Methodology

Research questions

In this chapter a suggestion is made for the methodology applied to approach the various challenges in this thesis. First an overview of the research questions is presented. These questions are the result of a preliminary research on the topic and are the direct representation of the objectives of this thesis research. Then the methods necessary to find answers to these questions are presented.

Main research question

Is it possible to envision existing cable net facade design to withstand blast loading, using a biomimetic approach? This question can be subdivided in literature research questions and design questions.

Literature research questions

- Could a spider web, as natural structure, provide an inspiration for cable net facades under special loading?
- Which properties of the spider web can be imitated on a building scale?
- Is the spider web, as a typology, a better idea to cope with blast loads than the existing orthogonal cable net structures?

Design questions

- Which design strategy can be applied for the analysis of cable net facade structures in the conceptual design stage?
- Is it possible to model a spider web structure using finite element modeling?

Methods

The purpose of the present work is to provide an integrated solution for the protection of the Market hall in Rotterdam during a potential blast explosion. The main idea lies in the construction of a flexible lightweight system that can withstand blast loading providing human safety in the building while at the same time the conceptual design is minimal according to the architectural trend of the times. Three main consecutive steps have to be taken towards that direction:

Step 1: Background Research

The background research concentrates on three main topics: Investigation of the biomimicry aspects of spider webs, review of the basics of blast loading and finally overview of the features of existing cable net façades. Investigation of the biomimicry aspects of spiderwebs. The study of the main aspects of spider webs is central so as their main aspects to be mimicked in the new design. The material and mechanical properties of the spider silk will be examined as well as their form.

Review of the basics of blast loading. In order to design for blast it is vital to determine the potential danger, the extent of this danger and the blast response of the building as whole.

Features of existing cable net façades and the existing Markthal facade. For redesign the Markthal façade a research on the architecture and pathology of the existing cable net façade in general and of Markthal specifically is necessary.

At the same time, since glass is a key factor for the success of this system, a brief but thoughtful research was made on the selection of the appropriate glass type as a cladding material.

Step 2: Simulation of the physical shape.

A parametric model in the form of a simplified spider web was made with the use of the Rhino software and the Grasshopper plug-in in combination with the kangaroo, so as to gain very quickly an overview of the response of the system under uniform vertical loading.

In a second phase hand calculations for the less favourable individual cable were made considering the whole system as a SDOF using the principles of quasi static analysis, assessing the behaviour of the blast load structure on the final stage.

Finally, a simplified FEM model using ANSYS software was made targeting to more accurate results of the final stages of the structure.

Step 3: Design

The focus of the design was mainly placed on the improvement of the blast performance of the system. However, a significant period of the thesis' time frame was dedicated for establishing appropriate energy absorption systems, so centrally on the façade and as locally on every individual cable. The final form of the facade aims to the incorporation of the blast resisting and aesthetic demands.

When the conceptual design was finalized, emphasis was given into designing the key-details for the structural feasibility of the façade, that are the connections between the main load bearing structure and the cladding / structural skin, in order to create a viable glass system in combination with an effective connection mechanism.

II. Background study

The background study concentrates on three main topics: Investigation of the biomimicry aspects of spider webs, review of the basics of blast loading and finally overview of the features of existing cable net façades.

7. Spider webs

7.1. Terminology

Orb webs are approximately planar structures that are distorted into conical shapes during insect impact and they are traditionally divided into 4 quadrants, each covering a 90° angle (Figure 7).

The name 'orb' is somewhat misleading in that the webs are rarely fully symmetric circles. Orb webs are instead typically elliptical with the southern quadrant being larger, having a more even mesh size and more radii than the other quadrants.

In Figure 7, the area A in the centre of the web represents the hub. Outside of the hub, the area B, is the free sector, which is a zone with no threads except the converging radii. Following this zone we find area C, representative of the capture spiral. The frame is symbolized by the letter D; it is the outer limit of the web and is attached to the surroundings with anchor threads. The radii (letter E) run from the hub to the frame and stand for the basic structural element of the web. If a radius splits into two before reaching the frame, it is referred to as a Y-shaped radius (letter F).

The area within the frame is called the web area, whereas the capture area is the area covered by the capture spiral (excluding the area of the free zone and the hub). Each loop of the capture spiral is called a spiral turn and the mesh size is the distance between two consequent spiral turns (area G) (Hesselberg & Vollrath 2012).

A variety of metrics quantify the sizes and shapes of orb webs using formulas to estimate the capture area, the web and hub asymmetry, as well as the capture length thread the mesh width. These formulas and more information are presented on the gray info boxes.

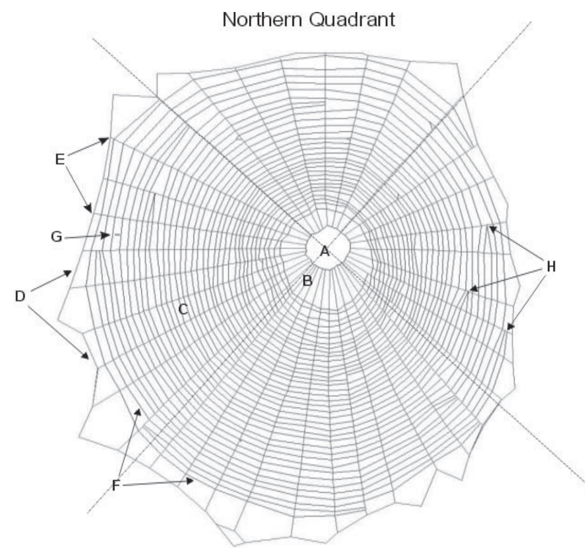


Figure 7. A digitised web of Araneus diadematus with letters referring to parts of special interest. The crossing lines split the web into 4 quadrants with the northern and southern quadrant emphasised. A) the hub, B) the free sector, C) the capture spiral, D) the frame, E) radii, F) spiral turns, G) mesh size and H) reverses. See the text for further explanations of these terms (Hesselberg & Vollrath 2012)

7.2. Construction sequence

Spider webs in contrast to man-made structures should be studied in combination with their builder. The understanding of the web construction requires study not only of the structure per se but also of the moving animal. Although the movement pattern of the spider during web construction resembles the final web structure, it does not perfectly match it since during construction the spider walks routes from which it later removes the threads and it also walks detours which are later bypassed by the threads. Computerised observation methods allow us to view the building behaviour on a macroscopic basis (total behaviour pattern) providing better understanding of the web construction.

Quantifying web shape

A variety of metrics quantify the sizes and shapes of orb webs (reviewed in part by Herberstein et al. 2000). The total capture area of an orb web, delimited by the outside of the capture spiral, is best measured directly from photographs, but can also be estimated through a variety of formula. Blackledge 2011 argues that the most efficient formula to estimate capture area is:

$$\text{Capture area} = \left(\frac{d_\mathrm{v}}{2}\right)\left(\frac{d_\mathrm{h}}{2}\right)\pi - \left(\frac{H}{2}\right)^2\pi, \qquad (1)$$

where dv is the vertical diameter of the web measured from the outermost row of capture spiral, dh is the horizontal diameter measured from the outermost row of capture spiral, and H is the average diameter of the hub and free zone, measured along the vertical axis (Figure 21).

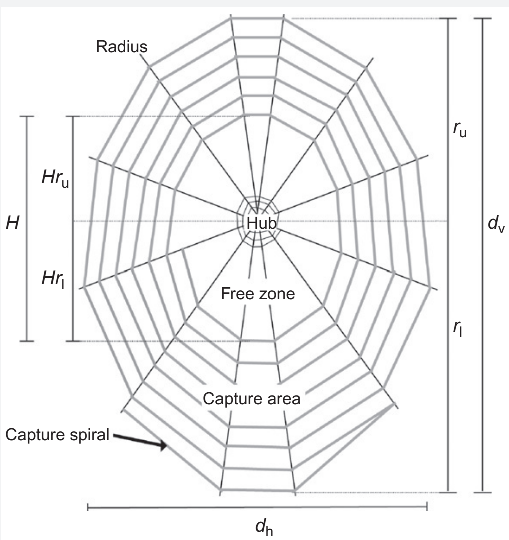


Figure 21. Parameterization of the capture surface of an orb web

Blackledge 2002 term the departure of the shape of the web from a circle as web asymmetry, which is calculated as: web asymmetry

$$\text{web asymmetry} = 1 - \frac{d_\mathrm{h}}{d_\mathrm{v}}, \qquad (2)$$

where dh is the diameter of the web along the horizontal axis and dv is the diameter along the vertical axis (Figure 21).

This index, also used by , departs from a value of zero and tends toward one in asymmetric webs, but may show negative values in horizontally exaggerated webs. Kuntner et al. 2010a, Kuntner et al. 2010b and Kuntner et al. 2008 termed a similar formula the ladder index (calculated as the ratio of web height to web width; Peters, 1937 named this Große Achse/Exploded view of the facade build-up-.e Achse), which tends to the value of one in symmetrical webs, but may reach values above five in strongly vertically elongated webs (e.g. Herennia; Kuntner et al. 2010b).

The hub asymmetry of an orb web quantifies the displacement of the hub from web's geometric center (Blackledge 2002) and is calculated as:

$$\text{hub asymmetry} = 1 - \frac{r_\mathrm{u}}{r_\mathrm{l}}, \qquad (3)$$

where ru is the length of the upper radius along the vertical axis and rl is the length of the lower radius (Figure 21).

All of the above measures of web geometry take into account only the actual capture area that is delimited by the inner and outermost rows of the capture spiral, even though the radii extend beyond them all the way to the frame.

Venner et al. 2001 reviewed formulae for calculating the capture thread length (CTL) of an orb web, and concluded that the most appropriate, consistent, and straightforward formula was:

$$\mathrm{CTL} = (1-a)\frac{\pi}{16}(N_\mathrm{v}+N_\mathrm{h})(D_\mathrm{ov}+D_\mathrm{iv}+D_\mathrm{oh}+D_\mathrm{ih}), \qquad (4)$$

where the correction factor a=0 for most species except the free sector of Zygiella (and similar genera), N is the number of spiral turns, Do and Di are the outermost and innermost diameters of the capture area, and suffixes v and h denote vertical and horizontal, respectively.

Note that Dov is equivalent to H in Figure 21. This formula does not take into account varying mesh width across the web, but nevertheless provides a good estimation of the total length of capture spiral in an orb web.

The mesh width (also called mesh height or mesh spacing) varies between closely related spiders. Mesh width is believed to greatly influence prey re-

We should mention here that different types of spiders produce different webs. However the basic procedure, as recorded by observations of the Araneus diadematus, serves sufficiently the purpose of this research. In Figure 8 we can see the proto-hub which consists of several radii before the beginning of the frame construction. The first frame thread works as the bridge thread and after its construction the spider moves the hub.

This new hub position is usually final. The primary radius constructed together with the bridge thread formed the constructional middle of the web. For the construction of both neighbouring secondary radii, this primary radius was used as the exit radius.

The drawings are based on recorded moves of the spider, with the threads reconstructed from those moves. In each picture, the moves of the spider are indicated with grey arrows (light grey – earlier moves; dark grey – later moves). The plain lines show the position of the threads when the "snapshot" was taken.

In Figure 9 the spider first walks out along an existing radius (the exit radius), pulling a dragline behind (A). When it reaches the edge of the web it may walk down a few steps to establish this dragline as a new radius (as shown in this figure). Next it walks back a short distance along this new (or the old) radius and attaches the frame-thread to be (B). Then it walks back to the hub and along the next lower radius to the edge of the web where it attaches the frame thread. Finally it returns to the hub via the newly laid frame thread (C).

In this instance of frame construction, the spider attached the new frame on the supporting structure; on returning it did not walk as far as it had walked out the first time and the spider did not move the frame thread on its return to the hub (Zschokke & Vollrath 1995).

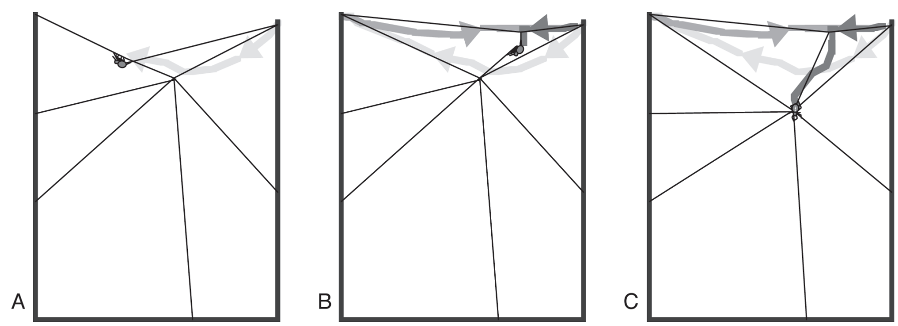


Figure 8. Construction of bridge thread and first proper radius in A. diadematus (Zschokke & Vollrath 1995)

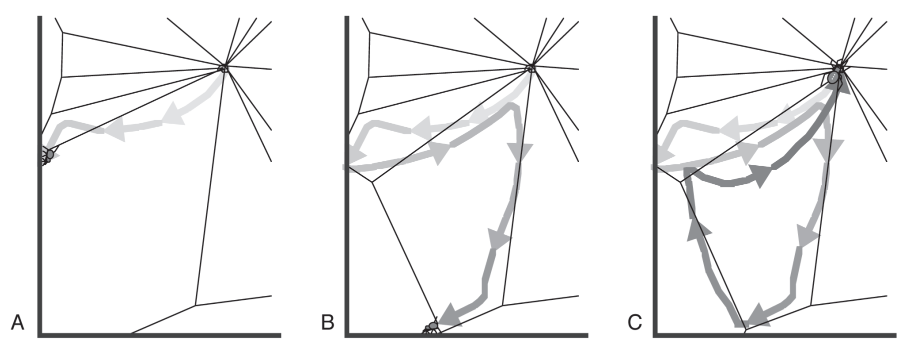


Figure 9. One possible way of Araneus diadematus to construct a frame. (Zschokke & Vollrath 1995)

tention, and thus the sizes of prey targeted by webs, although these relationships are difficult to estimate (Blackledge et al 2006). A tight mesh provides more silk per unit area for kinetic energy absorption as well as more stickiness per area, and may well result in more effective snare for relatively larger prey compared to a wider meshed web.

However, this generality could easily change if threads differ in diameters or material properties.

Mesh width is typically measured as the average distance between rows of capture spiral along a particular axis of the web (usually the vertical) and is calculated as:

$$\text{mesh width} = \frac{1}{2}\left(\frac{r_u - Hr_u}{S_u - 1} + \frac{r_l - H_{rl}}{S_l - 1}\right), \quad (5)$$

Where ru is the upper radius length, Hru is the distance from hub to innermost upper capture spiral, Su is the number of rows of capture spiral in the upper half of the web, rl is the lower radius length, Hrl is the distance from hub to innermost lower capture spiral, and Sl is the number of rows of capture spiral in the lower half of the web (Herberstein et al. 2000); (Figure 21).

While commonly used, this mesh width index ignores that spacing between rows of capture spiral is rarely constant within an orb web and instead tends to increase from the hub outward.

One final consideration is that all of these formulae are designed to measure the geometries of orb webs. Capture area and CTL are often used as proxies for material or energetic investment in orb webs (e.g. Sherman 1994). However, this approach entails a critical assumption that the numbers and diameters of threads are identical between webs of different geometries. Given that spiders actively control both parameters during web spinning (see Section 4), this assumption is likely often violated. Energetic or material investment in webs is instead much better characterized as the total volume or mass of a particular type of silk in a web (Sensenig et al. 2012)

7.3. Material aspects

Spiders have drawn much attention from scientists in the past 20 years; most research on spider silk is motivated not by understanding biology, but rather by the biomimetic potential for development of the‘next generation’ of fibres for use by the military, industry and medicine (Altman et al. 2003). The prospects are not limited simply to the development of new fibres, but also include learning how to build robust but light-weight structures that mimic webs (Alam et al. 2007) new types of adhesives (Sahni et al. 2011) and even novel sensory structures (Barth 2002). However, the unfortunate disjunction between silk researchers in the lab, arachnologists studying webs in the field and engineers who design biomimetic structures, hampers both endeavours (Harmer et al. 2011).This study is an effort to combine the research that has been done in these different fields in order to offer a new-more complete-perspective on the material (spider silk) as well as the geometrical aspects (spider webs). In order for the reader to be familiar with the topic and the relevant terminology, a brief description of the main spider characteristics are given below.

Silk production

Silk production is a characteristic of all spiders and is also known among various mites, mantids, moths, beetles, etc. However, Biologists and biochemists define silks differently (Craig 2003).

To a biologist, silks are secreted, fibrous materials that are deposited or spun by organisms. To a biochemist, silks are protein threads composed of repeating arrays of polypeptides that contain both discrete crystalline and noncrystalline domains that are oriented around a fibre axis.

Insects, as a group, produce many different types of silks and fibrous proteins; however, each individual produces only one silk protein. Spiders also produce a variety of silks and fibrous proteins but, in contrast to insects, an individual spider may produce as many as nine different types of silks and fibrous proteins, each of which may be composed of more than one type of protein (Kovoor 1987).

The most investigated type of spider silk is the dragline or major ampullate (MA) silk that is secreted by the major ampullate glands of the spider. The dragline is used to support the spider when constructing a web and to prevent it from falling. This function results in mechanical properties combining a high Young's modulus with a high strength. Due to its size and accessibility the major ampullate gland has been the focus of most studies.

A second important type of spider silk is the flagelliform, spiral or capture silk. This type of silk is composed of an acidific glycoprotein, secreted from the flagelliform gland, and coated with glue from the aggregate gland what makes it sticky. The glue is not regarded as silk because it is composed of glycoproteins and other amino acids.

The flagelliform silk is exclusively used for the construction of the spiral components of the web. This function results in a fibre that is highly extensible and capable of absorbing the energy of the flying prey without failure. The functional role of the glue is believed to allow for more effective capture of prey.

Minor ampullate (MI) silk is the spider silk that is secreted by the minor ampullate glands and is a strong non-elastic deformable stretchable silk used in web formation (Colgin & Lewis 1998).

Spider silk as a natural fibre is a type of renewable source and a new generation of reinforcements and supplements for polymer based materials. Grouping different categories of natural fibres, they can be divided based on their origin, derivations of plant, animal and mineral types (Mei-po Ho et al. 2011).

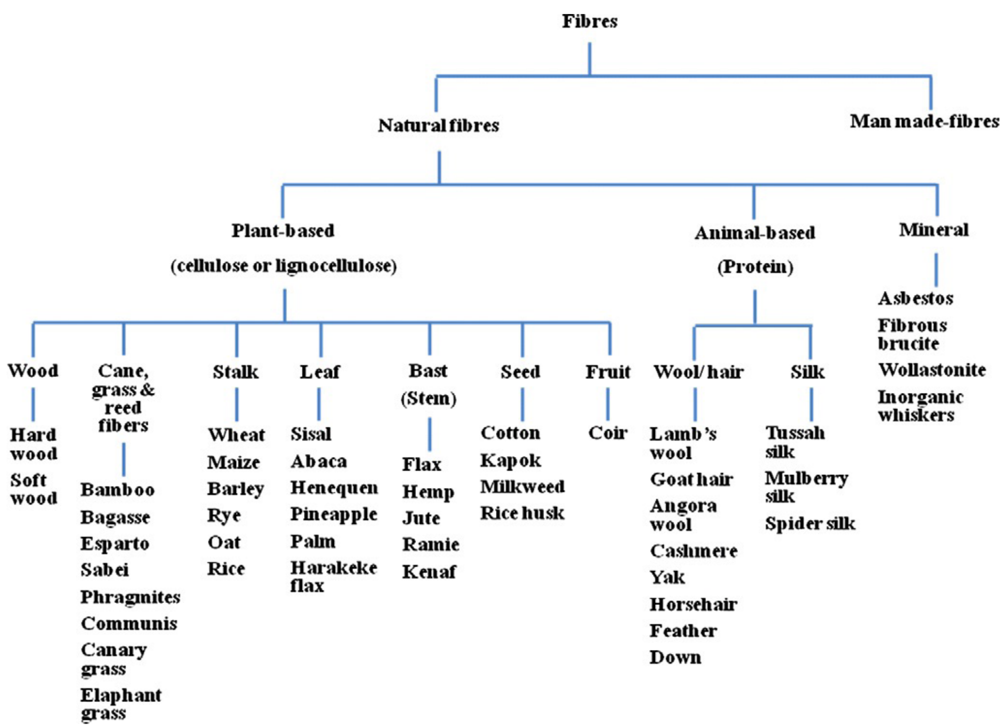


Figure 10. The classification of different natural fibres (Mei-po Ho et al. 2011)

Anatomy of a spider

Spiders (order Araneae) are air-breathing arthropods that have eight legs and chelicerae with fangs that inject venom. Their bodies have jointed limbs and heads that are composed of several segments. They consist of two tagmata, sets of segments that serve similar functions:

The foremost one, called the cephalothorax or prosoma, is a complete fusion of the segments that in an insect would form two separate tagmata, the head and thorax; the rear tagma is called the abdomen or opisthosoma (Figure 22).

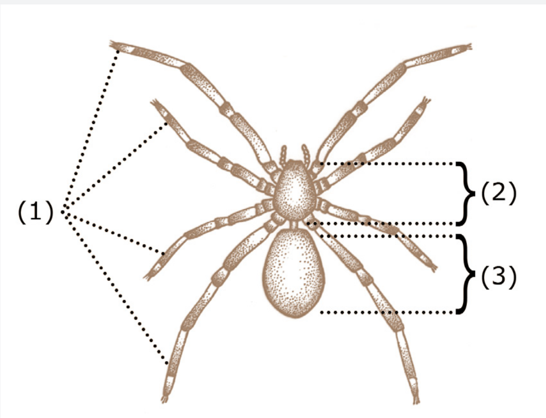


Figure 22. Spider anatomy: (1) four pairs of legs (2) cephalothorax (3) opisthosoma (abdomen) (Wikipedia 2013b)

The abdomen has no appendages except those that have been modified to form one to four (usually three) pairs of short, movable spinnerets; anterior, median and posterior which emit silk. Each spinneret has many spigots, each of which is connected to one silk gland.

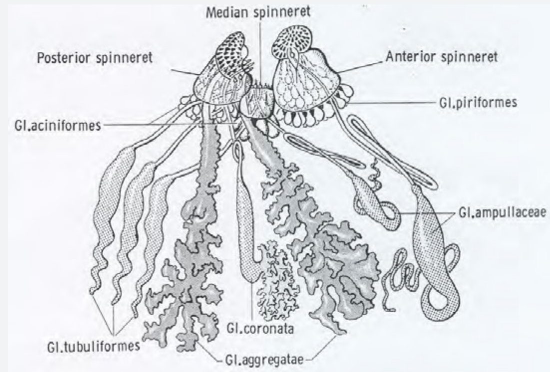


Figure 23. Types of glands and the respective silk use (Digid planet 2013).

There are at least six types of silk glands and they can be distinguished morphologically and histologically as: ampullate glands, aciniform glands, cylindrical or tubuliform glands, aggregate glands, piriform glands, and flagelliform (or coronate) glands (Van Nimmen 2006). Each type of gland secretes a different kind of silk with its own specific characteristics to perform a specific function. Figure 6 and Figure 23 give an overview of the different types of spider silks and their function for the orb-web weaving spider Araneus diadematus.

Gland	Silk Use
Ampullate (Major)	Dragline silk—used for the web's outer rim and spokes and the lifeline.
Ampullate (Minor)	Used for temporary scaffolding during web construction.
Flagelliform	Capture-spiral silk—used for the capturing lines of the web.
Tubuliform	Egg cocoon silk—used for protective egg sacs.
Aciniform	Used to wrap and secure freshly captured prey; used in the male sperm webs; used in stabilimenta
Aggregate	A silk glue of sticky globules
Piriform	Used to form bonds between separate threads for attachment points

Figure 24. Different types of spider silks and their function for the orb-web weaving spider Araneus diadematus (Digid planet 2013).

Morphology of a spider thread

As the morphology of the spider silk and the structure of the fibers control to a large degree its mechanical properties we discuss them briefly in this paragraph.

This (hierarchical) molecular order in spider silk is characterized by a number of various similar structural and micro structural models.

The common morphological entity in all textile fibres, both natural and manufactured, is the fibril, which is an assembly of molecules. The fibril of the spider silk is supposed to consist of a further nanofibrillar structure. The conformation of the molecules and their spatial arrangement into the fibrils differ from fibre to fibre and determine to a high extent its mechanical behaviour (Gupta 2000).

Concerning the structural model, a group at Dupont de Nemours (Li et al. 1994) has observed a highly organized skin-core structure for the dragline silk fibre of Nephila clavipes with the use of AFM (Atomic force microscopy). According to this model, the core consists of pleated fibril-like structures, which are arranged in two concentric cylinders (Figure 12).

Figure 11. Spider silk gland spigots (Dennis Kunkel Microscopy Inc. 2013)

This basic structure is later confirmed by other authors (Krink & Vollrath 1996 and Frische et al. 1998). Vollrath further proposed that the tube or skin seems to consist of twisted bands of microfibrils and is covered by an outer waterproof coating. Also an inner membrane between skin and core would be present, as presented.

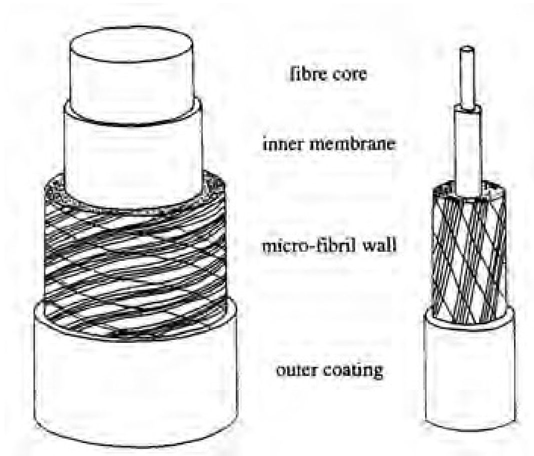


Figure 12. Skin-core model as proposed by (Krink & Vollrath 1996)

Regarding the micro structural model, the first very basic model of silk was introduced by Termonia in 1994. The model suggested crystallites embedded in an amorphous matrix interlinked with hydrogen bonds.

However, over the years with the development of technology this model refined and semi-crystalline regions were found (Figure 13) as well as a fibrillar skin core model suggested for spider silk, later visualized by AFM and TEM.

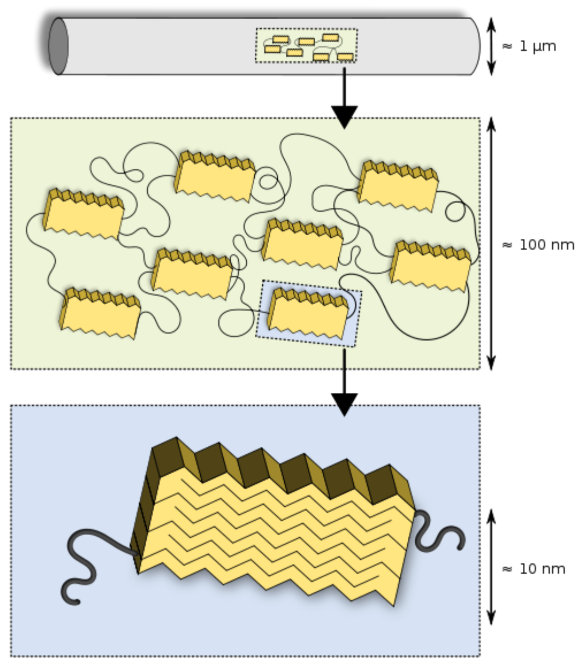


Figure 13. Structure of spider silk. Inside a typical fiber there are crystalline regions separated by amorphous linkages (Digid planet 2013)

Definition of Tensile properties

Each spider and each type of silk has a set of mechanical properties optimised for their biological function. Most silks and in particular dragline silk have exceptional mechanical properties. Silk mechanics is normally described in terms of stress, strain, toughness (work of fracture) and density (Digid planet 2013).

From the stress-strain curve, the following properties are determined by illustration:

1) Breaking stress or tenacity: ratio of a yarn's breaking force to its linear density.

2) Strain at break or breaking strain (%): increase in length of a specimen produced by the breaking force, expressed as a percentage of the original nominal length.

3) Work to rupture: area contained by the force-elongation curve up to the point where the breaking force is reached, this is a measure of the toughness of a fibre. It can also be expressed in cN/dtex by dividing this value by the gauge length (in cm) and by the linear density (in dtex).

4) Elastic Modulus: defined as the modulus in the elastic range of the diagram in which strain changes are still reversible. It is calculated from the slope of the initial straight line portion of the stress-strain curve.

5) Post-modulus: defined as the modulus in the strain hardening zone. It is calculated from the slope of the straight line of the zone following the yield region, where the stress again is proportional to the strain values (Van Nimmen 2006).

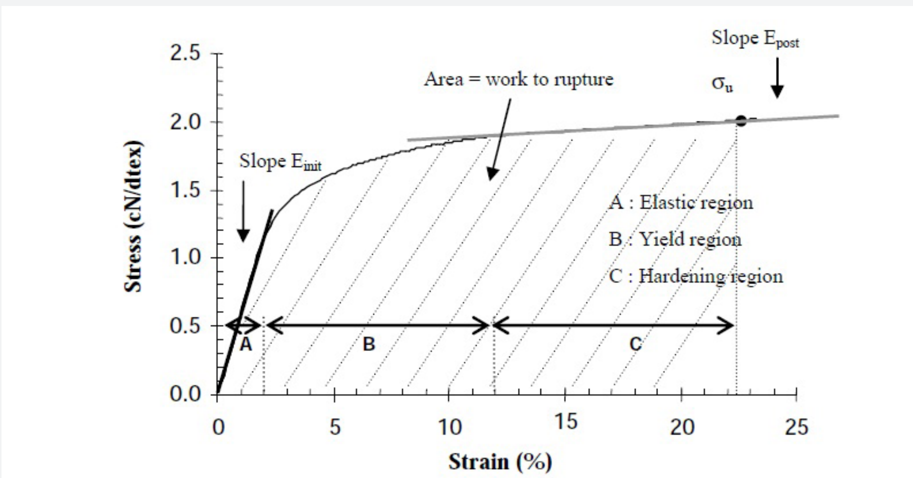


Figure 25. Stress–strain curve typical of most dry spider silks (Van Nimmen 2006).

The thread performance is determined by the total numbers and sizes of fibres in a thread, by intrinsic material properties but also by the bond between the fibrils (Boutry et al. 2008).

A multifibrillar fibre with weak bonding between fibrils offers a number of possible mechanical advantages over a solid fibre of the same total cross sectional area. One is that the fibre will have greater flexibility so that it requires a lower moment to bend through a given radius of curvature (Hull 1995).

Tensile properties

In vitro tests of spider strings under simple tension in comparison to other textile fibers show that spider dragline silk stands out in comparisons of engineering stress-strain curves Figure 14.

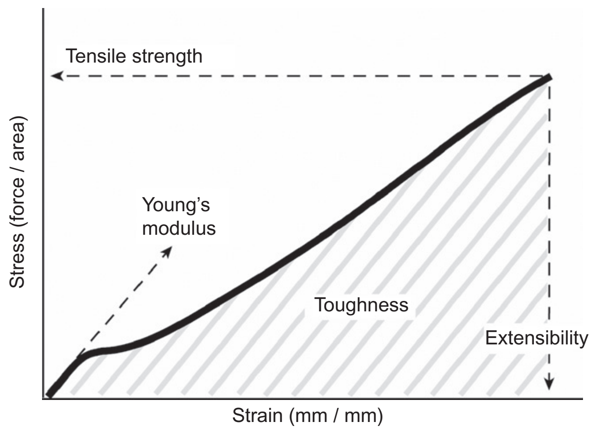


Figure 14. Definition of tensile properties

Kevlar is stiffer (modulus of 112 GPa) and stronger (failure stress of 3 GPa) than dragline silk (modulus of about 10 GPa and strength of about 1.5 GPa) but golden orb-spider dragline silk is tougher in terms of energy to breakage (Kevlar 40 MJm –3 and dragline silk up to about 250 MJm –3).

Spider dragline silk exhibits the best balance of strength and toughness (Vollrath et al. 2013a).

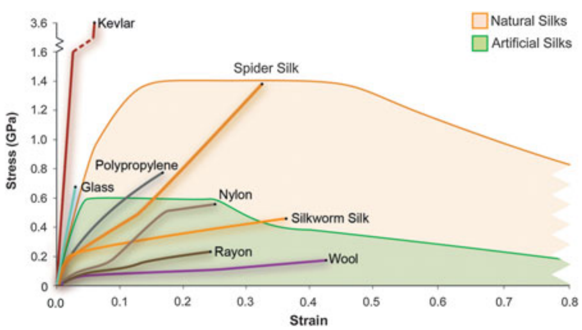


Figure 15. Silk tensile properties in comparison to other industrial and natural fibers and artificial silk (Vollrath et al. 2013a)

The shape of the stress-strain curve for each fibre is determined by the aspects of its structure that permit or resist polymer straightening and movement of the polymers relative to each other (Hatch 1993).

As we have already mentioned the structure of spider silk may be considered as a hierarchical composite consisting of a liquid crystalline phase which is organised into a well-ordered helical fibrillar reinforcement structure. The helical fibrils are embedded in a matrix which consists of a network of inter-fibril linkages formed by hydrogen bonds. The high modulus in the initial region of the stress-strain curve reflects the combined contribution of the fibrils and the inter-fibrillar network of hydrogen bonds.

(Ko 1997) offered a structural basis for the stress-strain behaviour of dragline spider silk emphazing the role of a fibrillar structure on the stress-strain behaviour. On rupturing of the inter-fibrillar linkages, the stress-strain curve exhibits a pseudo yield behaviour due to re-orientation of the fibrils. As these helical fibrils are straightened a gradual increase in modulus can be seen until it reaches a maximum.

This is followed by the gradual rupturing of the fibrils and at the point at which permanent deformation starts to take place, called the yield point, the interchain bonds in the amorphous regions can break and the polymer chains begin to slip by each other.

At that point, additional stress easily extends the fibre, resulting in a flattening of the stress-strain curve. The slope of this flattened region largely reflects the strength of intrafibre bonding: the greater the bonding strength, the greater the slope of this segment.

Following hardening, the internal structure of the fibre begins to give way catastrophically and the rupture point is reached. The polymers have either slipped by each other because the applied stress is greater than the intrafibre bonding force or the applied stress has surpassed the strength of the polymers themselves, causing them to rupture. With respect to the strain-at-break, fibres that are highly-oriented and crystalline and have strong intrafibre bonding and/or straight polymer configuration tend to exhibit lower strain-at-break values (Van Nimmen 2006).

Transverse Compression Properties

The behaviour of the spider silk has also been tested under transverse compression. The compression tests were carried out by placing a single fiber between a flat and a mirror-finished steel plate and a mirror finished 0.2 mm square compression plane Figure 16 (Ko & Jovicic 2003).

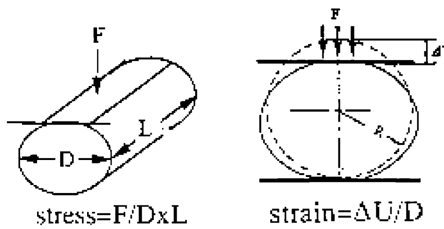


Figure 16. Compression test (Ko & Jovicic 2003).

The spider silk fibers were subjected to transverse cyclic loading at a compressive speed of 0.3 cm/s under ambient and wet conditions. The compressive modulus of the fiber tested in ambient condition was 0.58 GPa and the fiber experienced a high degree of permanent deformation (≈20%). As shown in Figure 17, the ability of spider silk to deform transverse compression is higher than all of the other textile fibers.

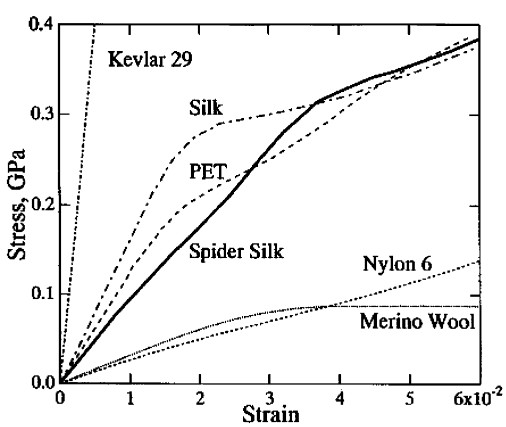


Figure 17. Compressive stress-strain behavior of N. clavipes spider silk (Ko & Jovicic 2003).

This indicates a high level of anisotropy and transverse ductility, offering superior ability to absorb energy under deformation in the transverse direction such as in the crossover between silk fibers (Ko & Jovicic 2003).

Simulation tests

In order to support and complement the experimental results, simulations of the spider silk using finite element methods (FEM) have been employed.

To explore the role of material properties and architectural design in spider web structural integrity and mechanical performance the elastic response of a simulated web structure was observed for an impact velocity of 1 m/s and a duration of 0.01s.

The total strain energy was evaluated as a function of time for different web materials listed in Figure 18 (Cranford et al. 2012).

material	density [kg/m³]	tensile modulus E_L (GPa)	Poisson's ratio ν	strength σ (GPa)	strain %
spider silk	1098	0.003	0.49	0.58	150
viscid dragline		34		1.75	26
Kevlar 29	1450	45	0.34	2.8	3.6
spectra	970	101	0.4	3.0	3.4
PBO	1540	270	0.35	5.8	3.5

Figure 18. Engineering Properties of the compared materials (Ko & Jovicic 2003).

Moreover the finite element analysis , as one can see in Figure 19 predicted that the spider web would be able to stop the impacting bug without failure, while at the same time, for the same boundary and loading condition, simulations showed that the web made of PBO material would be perforated (Ko & Jovicic 2003).

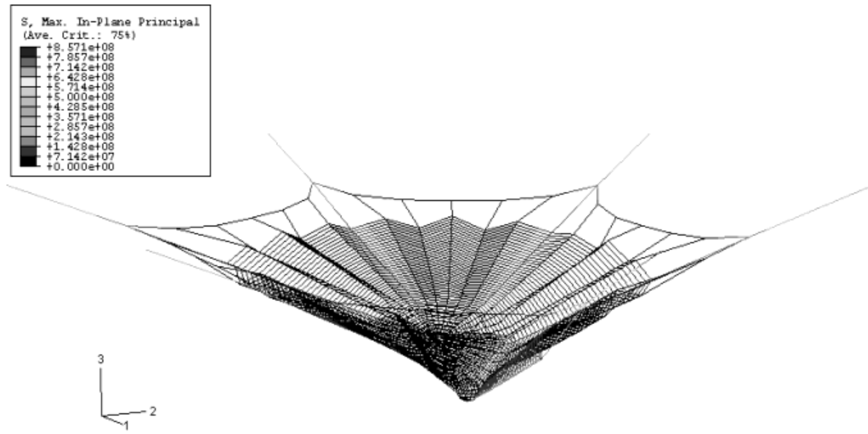


Figure 19. Principle stress distribution during simulated impact on spider silk web (Ko & Jovicic 2003).

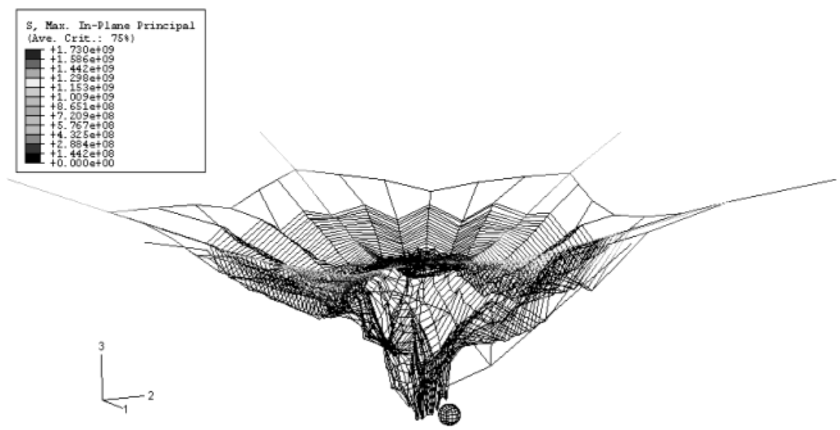


Figure 20. Principle stress distribution during simulated impact on PBO web (Ko & Jovicic 2003).

7.4. Structural behaviour

Apart from the remarkable material properties of spider silk, spider webs are natural example of a special class of pre-stressed systems called tensegrity (tensional integrity) structures. These structures represent a unique blend of geometry and mechanics, resulting in highly efficient structures due to the optimal distribution of structural mass (Ko & Jovicic 2003).

The lightness of these structures places them in the same class as cable and membrane systems. The self-stressing nature, which provides their rigidity, provides spider webs the mechanism for efficient and economic means of balancing the stresses induced. As Ko & Jovicic 2003 claims:

> *"An understanding of the interaction of material properties and structural geometry may shed light on our ability to design the next generation of ultra-lightweight, large area space structures"*

The team of Markus Buehler, an associate professor of civil and environmental engineering (CEE) at MIT, applied their analysis to the structure of the webs themselves, finding evidence of the key properties that make webs so resilient and relating those properties back to the molecular structure of silk fibers. This study finds;

> *It's not just the strength of the silk itself; the silk's way of stretching and the structure of the whole web help it resists damage (Feng et al. 2011)*

In Nature it is rare to find a perfectly intact web but the structure usually remains functional for a spider's use. So as to investigate further this observation, assessing a web's ability to tolerate defects by removing web sections (silk threads) and applying a local load, Buehler and his colleagues developed a web model.

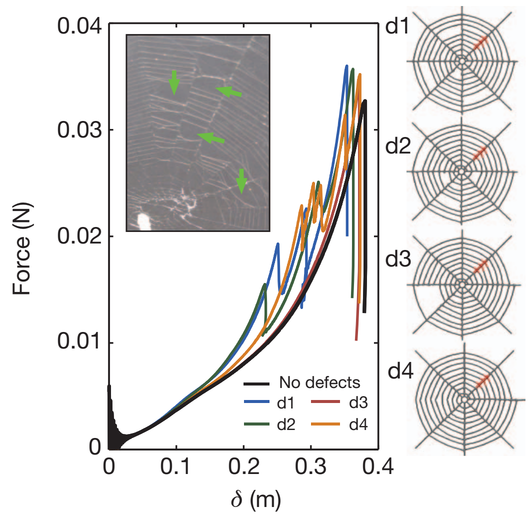


Figure 26. Force–displacement curves for loading a defective web (results for model A; loaded region shown in red). Case studies include missing spiral segments (d1 to d3) and a missing radial thread (d4). The inset to c shows the in situ orb web as discovered, containing many defects (marked by green arrows) (Cranford et al. 2012).

However as it is unresolved whether this behaviour is unique to silk-like materials or a result of the web's architecture (that is, a property of the construction material or of the structural design) the response of webs constructed from three different types of fibres with distinct mechanical behaviour systematically compared.

The simulation results that the relative size of the damage zone is a function of the material stress–strain relation and enhanced by the discreteness of the web. The the nonlinear stiffening behaviour of spider webs is essential for localizing damage and ensuring that a loaded thread becomes a sacrificial element while the majority of the web remains intact (Cranford et al. 2012).

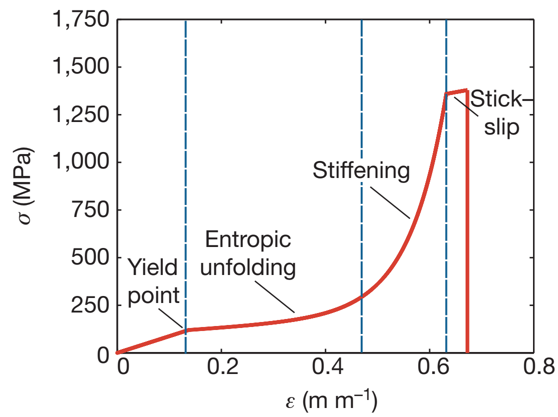


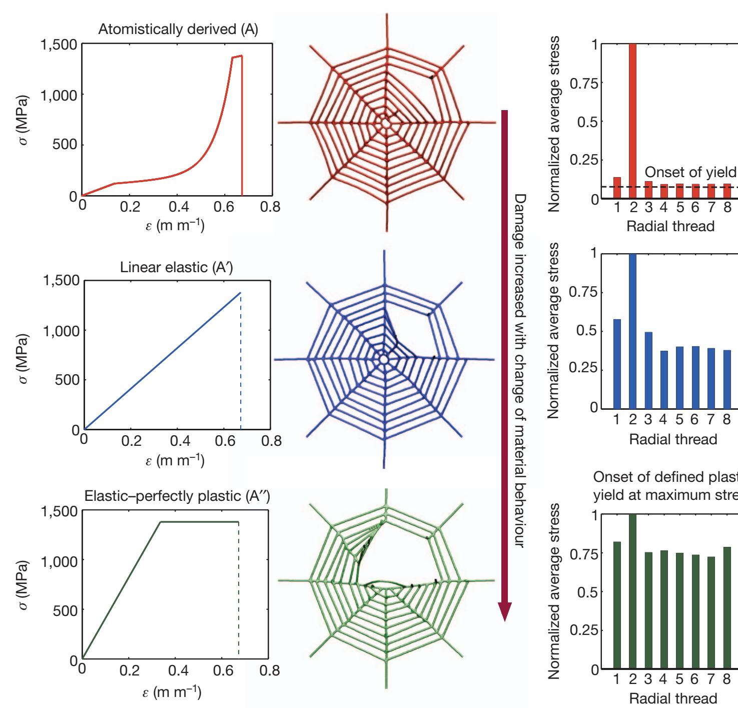
Figure 27. Material behavior of drag-line spider silk, web model, and behavior of webs under load. a, Derived stress–strain (s–e) behavior of drag-line silk, parameterized from atomistic simulations and validated against experiments16,17. There are four distinct regimes characteristic of silk16,17. I, stiff initial response governed by homogeneous stretching; II, entropic unfolding of semi-amorphous protein domains; III, stiffening regime as molecules align and load is transferred to the b-sheet crystals; and IV, stick–slip

Buehler's research is mostly theoretical, based on computer modelling of material properties and how they respond to stresses. In this case, to test the findings, he and his team literally went into the field: They tested actual spider webs by poking and pulling at them.

The in situ experiments were in qualitative agreement with the simulations: they confirmed the prediction that failure is localized when loading either a spiral or radial thread (MITnews 2013).

In conclusion, according to this study, the remarkable strength, toughness and extensibility of individual spider silk threads are thus not the dominating properties that underpin the excellent structural performance of a spider web. Rather, it is the distinct nonlinear softening and subsequent stiffening of dragline silk that is essential to function, as it results in localization of damage to sacrificial threads in a web subjected to targeted (local) loading while minimizing web deformations under moderate wind (global) loading (Cranford et al. 2012).

Figure 28. Web response for varied silk behaviour under targeted (local) and distributed (global) loading. Comparison of failure for derived dragline silk, linear elastic and elastic–perfectly plastic behaviours (left, models A, A' and A"). Comparison of failure (centre) confirms localized stresses and minimized damage for the natural nonlinear stiffening silk behaviour. The average stress of each radial thread (bar plots, right) reflects the nonlinear deformation states in the silk. When load is applied locally to a radial thread, other radial threads not subject to applied force reach a stress corresponding to the onset of yielding (that is, regime II in [Figure 28]). The elastic–perfectly plastic behaviour leads to an almost homogeneous distribution of stress (Cranford et al. 2012).



Energy dissipation

Orb webs interact mostly with flying and jumping insects that cannot be captured unless the webs successfully dissipate their kinetic energy without breaking. Indeed, the importance of stopping insect flight is often cited as a major selective factor favouring the evolution of the impressive material properties of the silks in orb webs (Denny 1976).

However, the work performed by an orb web during prey capture may be determined not only by the intrinsic material properties of silk threads, but also by how those threads are interconnected and even by the aerodynamic drag of the web moving through the air (Sensenig et al. 2012).

Energy dissipation by orb webs can be partitioned into three components:

(i) internal dissipation within the radial silk

(ii) Internal dissipation within the capture spiral silk and

(iii) aerodynamic drag as the web moves or oscillates during prey impact.

Sensing and his team measured the strain of silk in whole orb webs during simulated prey impacts and calculated the work performed these three components.

According to this experiment both aerodynamic damping and the capture spiral silk usually play only a minor role in energy dissipation during prey capture. Orb webs instead rely upon internal dissipation of prey energy by radial silk for up to 98 per cent of the work of stopping flying insects.

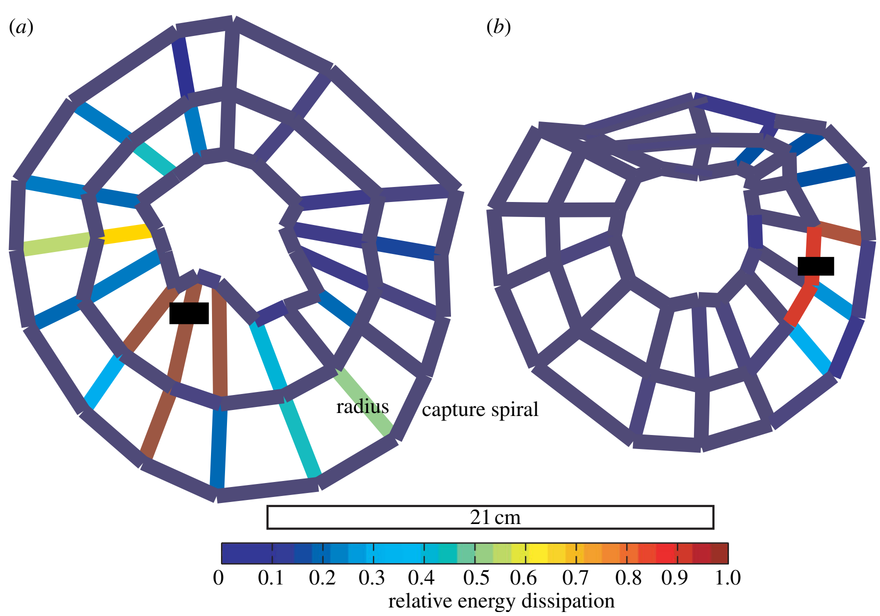


Figure 29. Energy absorption colour scale is normalized to the web region absorbing the highest energy. Aerodynamic dissipation for each segment was less than 0.1 relative energy, and is therefore not depicted. The inner-, middle and outer-most rows of capture spiral are summarized together. (a) Large web of A. trifolium (21 cm wide, spider weight 1270 mg) catching a balsam block (98 mg) shows that radii far from the impact site absorbed significant energy. (b) A slightly smaller web of Verrucosa arenata (21 cm wide, spider weight 56 mg) slowing, but not stopping, a balsam wood block (30 mg) shows that radial and capture spiral silk absorbed equivalent amounts of energy, with little role played by aerodynamic drag. The block broke through the web but was slowed from 2 to 0.3ms21 (Sensenig et al. 2012).

For most impacts, internal dissipation by capture spirals and aerodynamic dampening was negligible compared with internal dissipation by radii. Radial threads could account for 100 per cent of the absorbed prey energy in six of eight trials.

For the internal capture spiral dissipation and aerodynamic dissipation, the upper uncertainty never overlapped with 100 per cent, indicating that those routes were always insufficient to account for web function.

Connections

(based on Eberhard 1976)

According to Eberhard Orb webs are seen to be extraordinary sophisticated traps even in their microscopic details; they are constructed such that nowhere in the supporting framework (the hub excepted) do more than three elements meet at a junction.

Spiders typically interconnect threads in webs using piriform secretions, creating extremely durable bonds. However, capture spirals are attached to radii using a unique 'sliding connection' .

Sliding connections break under loading in such a way that adjacent segments of the capture spiral are freed to slide through the junction before the thread breaks. This distributes energy across a greater volume of capture spiral and prevents the capture thread from breaking, unless its loading continues to increase.

Araneid webs were observed under a dissecting microscope and Figure 30 represents the macroscopic results of pulling on sticky spiral threads and specifically the conversion of zero junctions to the pulley form when a segment of Araneid sticky spiral is pulled with increasing force.

> *Non-zero are the junctions in which the sticky spiral zig-zags are parallel to the radius for a short distance while Zero are the junctions in which the sticky spiral continues directly across the radius.*

The Figure 30 shows a pull approximately in the same plane of the web, however same results obtained when the sticky spiral was pulled perpendicular to the plane.

The conversion of the non-zero type of attachment involves the most complex series of evens. Figure 31 illustrates some of the microscopic events associated with the conversion of a non-zero sticky spiral-radius junction to the pulley form in a web of Metazygia sp.

Non-zero junctions could be converted to pulley forms by pulls from either side. If both sides of the attachment were carefully pulled simultaneously in a direction approximately parallel to the radius, it was possible to create a pulley attachment in the other sense, with the sticky spiral sliding up and down the radius than across it.

Some details of the mechanisms of the conversion of junction to the pulley form are still not clear, but two general statements can be made.

First, the material cementing the spiral to the radius apparently sticks more tightly to the radius than to the spiral. When the sticky spiral is pulled of one side of the junction it is always the sticky spiral rather than the radius which eventually slides through the attachment. The attachment to the radius can only be broken by carefully stressing both sides of the junction at once.

Secondly, cement's bond to the radius: too weak in the case of a stress perpendicular to the plane of the web , the sticky spiral will break free of the radius: too strong the sticky spiral will rupture before the cement's bond to the sticky spiral breaks (i.e. before the junction converts to the pulley form)

The conversion of a non-zero junction may represent a delicate adjustment of bond strengths: when the junction is first stressed perpendicular to the web plane, the bond to the radius is relatively weak, and the spiral begins to rip away; but then presumably because the cementing substance accumulates at the point the attachment to the radius apparently gets stronger, the spiral ceases to rip away, and eventually the bond between the cementing material and the sticky spiral breaks, converting the junction to the pulley form.

The sliding attachments described above have considerable functional significance in orb webs. The pulley form sticky spiral-radius junction is that sticky spirals are better able to stop prey: before a given segment of spiral is over-extended, it is lengthened by the addition of thread from adjacent segments, and its breaking elongation is thus increased.

At the same time, the spiral is not detached from the radii, and the prey is thus kept in the vicinity of the web where it can become entangled in other threads and captured.

It should be noted that although sliding attachments increase the spiral's ability to slow and stop moving objects, they do not strengthen the web in the sense that they allow it to support heavier objects hanging in it. The breaking tenacity is a function of a thread's diameter but not of its length.

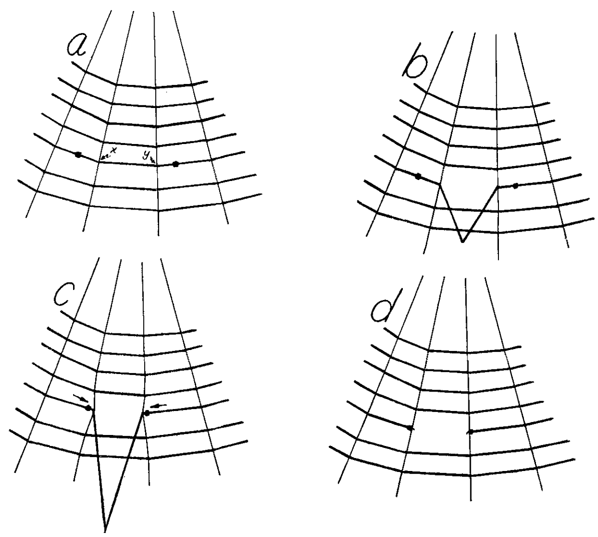


Figure 30. (a) Low stress: the segment being pulled was stressed, the radii on either side were not displaced. (b) Higher stress: radii slightly displaced, attachments of the sticky spiral to the radii partially ruptured. (c) Attachment: broke in a way which did not free the sticky spiral from the radius but it permitted the thread from the adjacent segments of the sticky spiral to pass through the attachment (pulleys attached to the radii at x and y). (d) Additional tension: stressed segment broke the two loose ends : contracted to a fraction of their former length (Eberhard 1976).

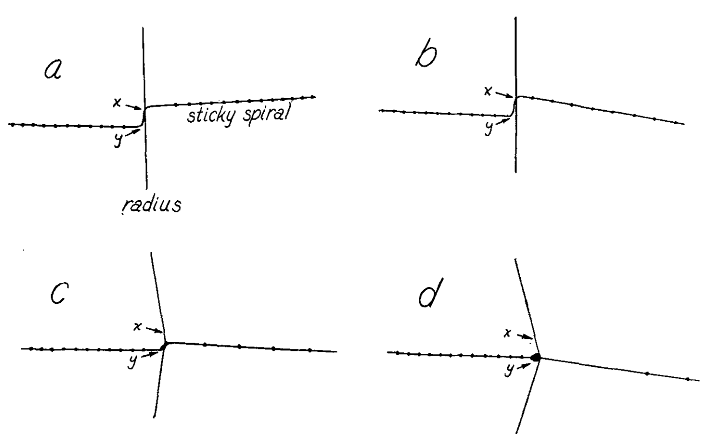


Figure 31. (a) Segment of sticky spiral was tensed. (b) First simply elongated, no change in the junction. (c) Greater stress: spiral elongated, more tipped away from one side of the junction; the material which had been cementing the junction accumulated near the one end of the junction. (d) Tension increased: sticky spiral: stopped ripping away from the radius but instead the junction converted to pulley form ; sticky spiral baseline flew through it; the balls of glue did not pass through the junction, accumulated in a growing lump left of the radius (Eberhard 1976).

Structural efficiency

Within the constraint of an overall planar construction the individual elements of an orb-web could be arranged in a myriad different ways. Of these possible arrangements only a very few are found in nature.

Further explanations for the configuration of the web involve the mechanics of web function and the manner in which the physical properties of spider's silk are suited to this function. DeWilde (1943), Savory (1952) and others have noted a distribution of the numbers of strands found in threads forming different parts of the scaffolding of orb-webs. For A. sericatus the radii typically contain 2 strands; frame threads, 4-8 strands; and guys, 8-10 strands.

This ordered partitioning of the number of strands and thereby the cross-sectional areas of the threads found in different elements suggests the application of a theory of minimum volume design known as Maxwell's lemma (Parkes 1965) which states that if every member of a structure built of one substance is under tension such that the stress in all members is equal and equal to the breaking stress of the material, the structure is built with the minimum volume necessary to resist the forces causing the tensions in the members. Essentially the theory states that if a structure is designed such that, when loaded to the breaking point, every member breaks at once, the material from which the structure is built is being used to its maximum capacity and the least amount of material is needed (Denny 1976).

The web does not strictly meet the criteria of Maxwell's lemma. While all the members of the web are in tension, the stress varies between the elements. The differences in stress, however, are much less than the differences in tension. To the extent to which the stresses are made equal the web approximates a minimum volume structure under Maxwell's lemma. Witt (1965) points out that orb-weavers neither run out of silk while building a web, nor at the end of construction have a large amount of silk left over. Thus, working with a set volume of material, the spider apportions this material at close to its maximum advantage (Denny 1976).

7.5. Production aspects and applications

Spiders, unlike silk worms, are territorial predators that are hard to farm to produce its silk. Since around the 1990 the use of genetic engineering techniques has developed spider silk industrial engineering. The invention of genetic modification in the late 1970's enabled scientists and engineers to devote much more effort to the field of spider silk reproduction, which could yield much more powerful materials. This major development in the field of genetics really opened the door to potential production of spider silk.

- Nexia: In 2002 Nexia, a Canadian biotechnology company had reported the production of industrial quantities of spider silk using milk from genetically engineered goats.
- Spinox: in 2003, David Knight, a pioneering researcher in spider silk, and his colleague Fritz Vollrath founded Spinox, a company focused on understanding and reproducing the mechanisms of the spider's spinnerets. They have patented a spinning nozzle that mimics some of
- the processes that occur within the spider's spinneret and produces tough fibers from a range of solubilized silks, recycled protein from other silks.
- David Kaplan: At the same time in Boston, Tuft University's David Kaplan was also working on recycling silkworm silk to produce research-grade, reconstituted silk resembling spider silk. Kaplan's process of reconstituting silks resulted in a sheet of crystalline silk proteins that can be stretched up to 300% into a water-insoluble film to be used like a sponge.
- Spiber Inc: In 2007, Kazuhide Sekiyama established Spiber Inc with fellow Keio University graduate students in 2007 creating a new material named QMONOS. Specifically, QMONOS, the protein they are working on from fibroin, can be transformed into fibre film, gel, sponge, powder, and nanofiber form. With the diffusion of QMONOS, they aim to step into a new era that utilizes the protein for material application.

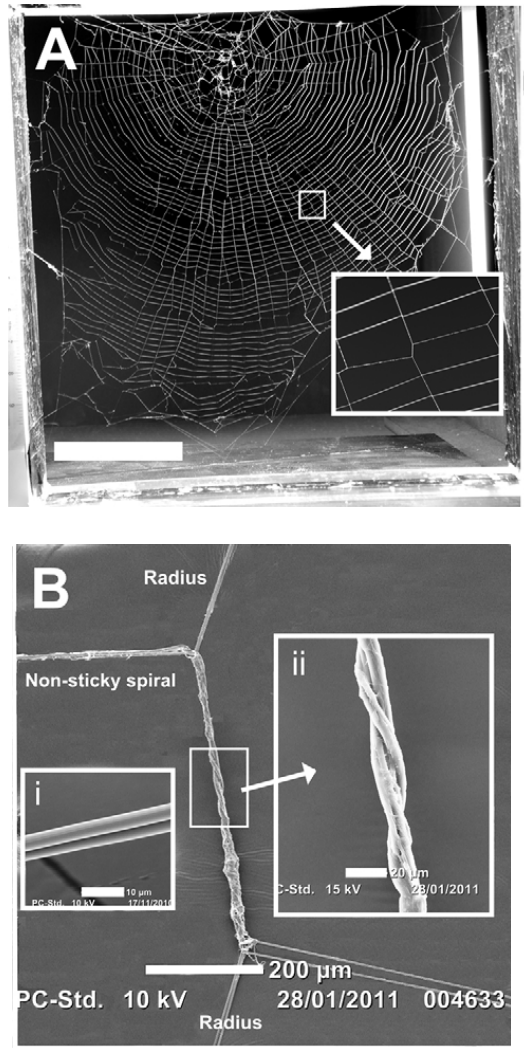


Figure 32. The structure of the non-sticky spiral. (A) A photo of a Nephila edulis web that shows the presence of the non-sticky spiral in the gaps of the sticky spiral. The inset shows a close-up of the non-sticky spiral, revealing its characteristic zigzag pattern. (B) A scanning electron microscopy (SEM) image of the junction between the radius (running vertically) and the non-sticky spiral (running horizontally) (Hesselberg & Vollrath 2012).

Currently, European, Asian and other research teams are working on the practical application of the spider silk but an innovative mass production method has not yet been proposed. Although at this moment the scenario of the massive production seems improbable, the manufacture strategy of the Spiber company is promising.

In cooperatrion with Kojima Industries Corporation, they are building a trial manufacture study plant capable to manage more than 100kg of QMONOS fiber per month. In 2015 the pilot plant will be completed and operated. The plan is to start production at a scale of 10 tons in the first year. After that they estimate that they will be able to start supplying worldwide. It will soon be time for the practical application of spider silk (Spiber 2013).

Undoubtedly the practical application of such a high-performance biomaterial will change common knowledge and it will realize the most innovative ideas of scientists and engineers. There is a vast amount of potential applications of the spider silk such as:

- Bullet-proof clothing
- Wear-resistant lightweight clothing
- Ropes, nets, seat belts, parachutes
- Rust-free panels on motor vehicles or boats
- Biodegradable bottles
- Bandages, surgical thread
- Artificial tendons or ligaments, supports for weak blood vessels.

However, in the building industry spider silk has not been yet considered as a building material and information about its potential use is limited. There are only ideas for constructing flexible bridge suspension cables made of spider silks but they remain still in a conceptual level.

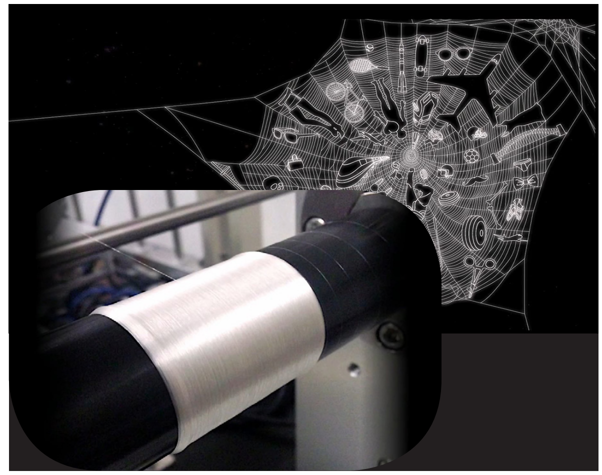


Figure 33. In a TEDx talk from Supaiba President and CEO, Sekiyama Kazuhide amazing development is displayed on the level of artificial spider silk QMONOS in fibre form and its future applications (TedxTokyo 2013)`

Use of Fibers as building components

There are a lot of attempts to commercially produce and use fibres in the building industry making us feel optimistic for the use of spider silk fibres in the near future. Hereby we discuss two cases that fibre cables have already been used in the building industry.

Elevator Cables

The KONE UltraRope™ is a new hoisting technology that could eliminate many of the disadvantages of conventional steel rope, and opens up new possibilities in high-rise building design. Comprised of a carbon-fiber core and a unique high-friction coating, KONE UltraRope is extremely light, which reduces energy consumption in high-rise buildings. The drop in rope weight means a dramatic reduction in elevator moving masses – the weight of everything that moves when an elevator travels up or down, including the hoisting ropes. Due to the significant impact of ropes on the overall weight of elevator moving masses, the benefits of KONE UltraRope increase as travel distance grows.

This rope is extremely strong and highly resistant to wear and abrasion. Elevator downtime caused by building sway is also reduced, as carbon fibre resonates at a completely different frequency to steel and most other building materials. While steel rope solutions require additional compensating ropes and sometimes must be shut down completely if the building sways at the same or greater frequency than that of the ropes, KONE UltraRope is much lighter and sways at much higher frequencies than the building, thus shut-down under these conditions is not required.

Since the rope has an exceptionally long lifetime – twice that of conventional steel rope – and thanks to the special coating, no lubrication is required in maintaining it, enabling further cuts in environmental impact.

This is achievable because the nature of the epoxy coating keeps the carbon fibre in a rectangular bar shape, transferring tension between carbon fibres. The fibres themselves have a high elastic modulus and good bending fatigue properties, and are inert in high temperatures – all serious considerations in tall buildings.

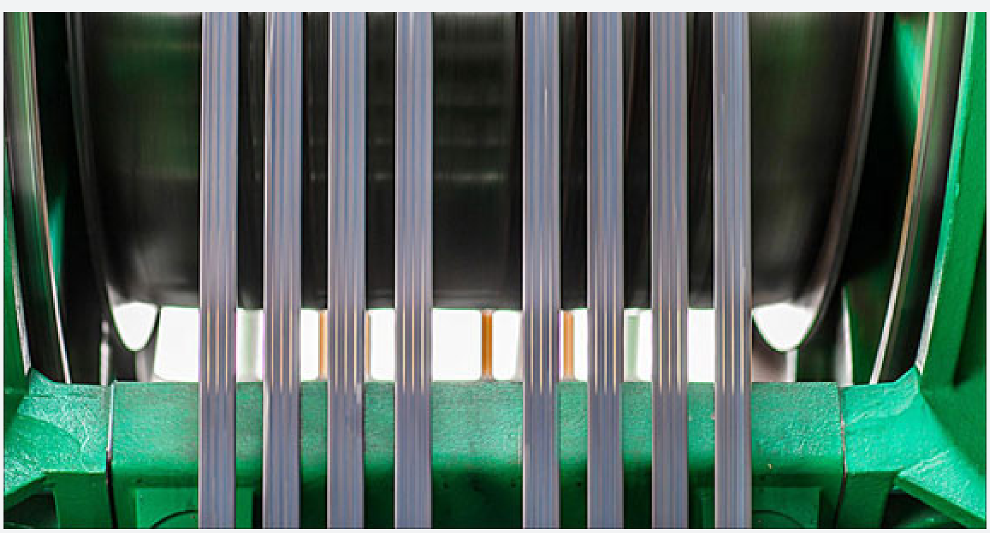


Figure 34. Kone Ultra Rope on a high-rise elevator spool

Environmental Considerations

There is an increasing recognition that buildings cannot be designed without consideration for their social impact on the environment. Waste and pollution affects communities.

Natural materials are generally lower in embodied energy and toxicity than man-made materials. They require less processing and are less damaging to the environment. The natural world has an immense amount to tell us about how to achieve sustainability. It uses energy far more efficiently and effectively and is capable of producing materials and structures that are far more benign than anything we have achieved in industry (Bhushan 2009).

Engineers can unravel the design principles behind the natural world creating new building materials and components contributing to more sustainable buildings. A good example is the spider silk due to the combination of its mechanical properties and the non-polluting way in which it is made. In contrast to the production of modern man-made super-fibres, such as Kevlar, that involves petrochemical processing which contributes to pollution, the production of spider silk is completely environmental friendly. In addition, the spider spins are completely biodegradable and totally recyclable fibers at ambient temperatures, low pressures and with water as solvent (Vollrath & Knight 2001).

There are consequently many advantages to copying the spider's silk and silk production capabilities: genetically engineered silk with specially tailored properties and spun using `green' processes could replace the ubiquitous plastics, which are often detrimental to the environment in both production and disposal (Vollrath & Knight 2001).

In Holland School of Applied Sciences, Delft

The glass facade at the INHolland School of Applied Sciences in Delft is a very interesting case study as it drives innovation introducing new structural concepts as well as new materials in the building industry.

The design goal was to create a very slender and transparent façade using composite materials in a structural way. However, all glass facades for larger spans need stabilizing systems for wind and deadweight loadings. Pretensioned glass façades accentuate lightness and maximum transparency due to minimal usage of obstructing profiles.

For this purpose the final concept introduced pre-tensioned aramide cables, run within the space of the insulated glass units for taking up the horizontal wind forces while deadweight suspension rods would take up the vertical deadweight of the system. The façade is exposed to deflections up to 300mm at windy days. The entire system has a structural depth of only 50mm with the height of the façade exceeding 13m.

More details about the innovations of this glass facade are given below (Octatube 2013).

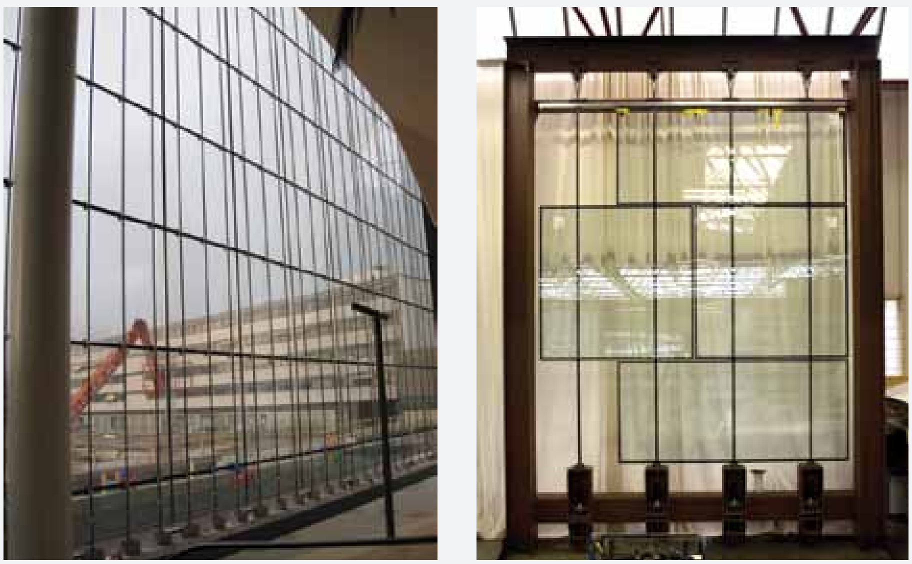


Figure 35. (left) facade elevation, (right) facade mock-up. The glass panes aren't threaded on the pretensioned cables like pearls on a string (Klein 2013)

Hi Tech Materials

The tension cables in the facade are made from aramid. Aramid is widely used in yacht design in the maritime sector. The cables have been extensively tested under supervision by Octatube.

The dutch INHolland 'Composietenlab', an institution specializing in experimenting with composites, proposed and tested the special tubes inside the cavity of the glass panels. The preconditions of this project resulted in the choice for composite tubes with 50% higher stiffness than steel.

Figure 36. Parts of the aramide cables, INHolland 2012

8. Blast Effects on buildings

8.1. Characteristics of explosions

An explosion is a very fast chemical reaction producing transient air pressure waves called blast waves. For a ground-level explosive device the pressure wave will travel away from the source in the form of a hemispherical wavefront until encountering obstructions in its path. The peak overpressure and the duration of the overpressure vary with the distance from the device. The magnitude of these parameters also depends on the explosive materials from which the bomb is made and the packaging method for the bomb. Usually the size of the bomb is given in terms of an equivalent weight of TNT.

Explosions can be categorized as physical, nuclear or chemical events. Examples of physical explosions include the catastrophic failure of a cylinder of compressed gas or the eruption of a volcano. In a nuclear explosion the energy released arises from the formation of different atomic nuclei by the redistribution of the protons and neutrons within the interacting nuclei. A chemical explosion involves the rapid oxidation of fuel elements forming part of the explosive compound (Mays & Smith 1995).

Blast loads are pressure waves caused by the rapid release of energy during a chemical reaction. The wave propagation is spherical in nature and dissipates with distance from the blast initiation. Although the spherical nature of a blast wave will cause differential pressures along the length of certain elements, such as columns, it can be assumed to be linear for simplification of design and analysis (Dick 2012).

Explosion classification

Combustion is the general term used to describe any oxidation reaction. In explosive materials that decompose at a rate much below the speed of sound in the material, the combustion process is known as deflagration. Deflagration is propagated by the liberated heat of the reaction. Detonation is the explosive reactions that produces a high-intensity shock wave. Most explosives can be detonated if given enough stimulus. The reaction is accompanied by large pressure and temperature gradients at the shock wave front and the reaction is initiated instantaneously. The reaction rate is described by the detonation velocity and lies between 1500 and 9000 m/s which is faster than propagation by the thermal process active in a deflagration.

Explosives classification

High explosives detonate to create shock waves, burst materials in which they are located, penetrate materials and when detonated in air or under water, produce air-blast or underwater pressure pulses. Low explosives deflagrate to produce pressure pulses of smaller amplitude and longer duration than high explosives.

Classification of these materials is generally based on their sensitivity to initiation. A primary explosive can be easily detonated by simple ignition from a spark, flame or impact. Mercure fulminate and lead azide are primary explosives and are found in the percussion cap of firearm ammunition. Secondary explosives can be detonated, but less easily than primary explosives. TNT and RDX are examples of secondary explosives, common for military applications.

Most explosives in common use are “condensed”: they are either solids or liquids. TNT (trinitrotoluene) is the most widely known example. There are 3 kinds of explosions which are: unconfined explosions, confined explosions and explosions caused by explosives attached to the structure (Yandzio & Gough 1999).

Terms and Definitions

Since this chapter introduces new terms, their definitions ,as they appear in the US General Administration Service code (GSA 1997), are presented here for the convenience of the reader.

- Explosive – Any substance or device, which will produce upon release of its potential energy, a sudden outburst of energy thereby exerting high pressures on its surroundings.
- Fully Thermally Tempered Glass (TTG) – This glass type has about four times the compressive strength of regular annealed glass. TTG is the same glass used by car manufacturers for side windows in automobiles. It is often called safety glass. The fully thermally tempered glass tends to dice into small cube like pieces upon failure.
- Incident Pressure – The overpressure (i.e., pressure above ambient) produced by an explosion in the absence of a structure or other object. Units are typically psi.
- Impulse – The area under a pressure-time waveform. Units are typically psi-msec.
- Interlayer – Any material used to bond two lites of glass and/or other glazing material together to form a laminate. For annealed glass the interlayer is normally a 0.030 in. thick polyvinyl butyral (PVB). For thermally tempered glass the interlayer is normally a 0.060 in. thick PVB. Some applications use a thicker interlayer (0.090 in. and 0.120 in. are sometimes used in special applications).
- Laminated Glass – Two or more plies of glass bonded together by interlayer(s). When broken, the interlayer tends to retain the glass fragments.
- Primary Fragments – Fragments produced directly from the contents or casing of an explosive device.
- Quasi-static – The late-time pressure produced in an internal detonation. It consists of slowly decaying shocks as well as gas pressures. The duration of the quasi-static pressure depends upon the vented area relative to the volume of the space affected. Units are typically psi.
- Reflected Pressure – Pressure pulse generated when a shock front impinges onto an unyielding surface. Units are typically psi.
- Setback – The distance between where a bomb is allowed and the target.
- Standoff – Standoff is synonymous with setback and may be used interchangeably with the term setback.
- Shock Front – A shock wave is a wave formed of a zone of extremely high pressure within a fluid, especially one such as the atmosphere that propagates through the fluid at supersonic speed, i.e., faster than the speed of sound. Shock waves are caused by the sudden, violent disturbance of a fluid, such as that created by a powerful explosion or by the supersonic flow of a fluid over a solid object. The rapid expansion of hot gases resulting from detonation of an explosive charge will form a shock wave. The leading edge of the shock wave is commonly referred to as the shock front.
- GSA- General Services Administration
- TNT – Trinitrotoluene (TNT), a pale yellow, solid organic nitrogen compound used chiefly as an explosive, prepared by stepwise nitration of toluene. Because TNT melts at 82º C (178º F) and does not explode below 240º C (464º F), it can be melted in steam-heated vessels and poured into casings. It is relatively insensitive to shock and cannot be exploded without a detonator. For these reasons, it is one of the most favored chemical explosives and is extensively used in munitions and for demolitions.

8.2. Response of a building to blast load

Blast loads are generally extremely intense but of very short duration. The dynamic characteristics of a structure and its capacity to absorb energy govern its response to an explosion. It is of course possible to calculate a building's natural period of vibration. Tall buildings have low natural frequencies and therefore a long response time in relation to the duration of the load. Individual elements like columns or beams however, have natural response times that may approach the loading duration. Elements made of reinforced concrete or steel are able to absorb a lot of strain energy due to their ductility. In other words, they can deform substantially without breaking. Elements made of brittle materials like glass on the other hand fail suddenly, with small prior deformation.

Flexible components like floors absorb a big part of the delivered blast load energy. Short span, lightweight elements are poor energy absorbers, conventional glazing components being therefore inappropriate for dealing with blast loads.

It should also be noted that, when larger explosions occur the structure is affected as a whole not only by the blast wave, but also through ground-shock.

Unconfined explosions can occur as an air-burst or a surface burst. In an air burst explosion, the detonation of the high explosive occurs above the ground level and intermediate amplification of the wave caused by ground reflections occurs prior to the arrival of the initial blast wave at a building. As the shock wave continues to propagate outwards along the ground surface, a front commonly called a Mach stem is formed by the interaction of the initial wave and the reflected wave.

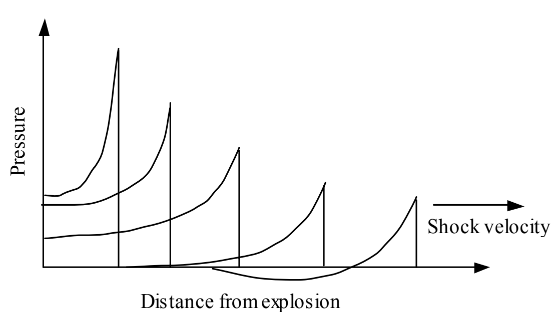


Figure 37. Blast wave propagation (Ngo et al. 2007).

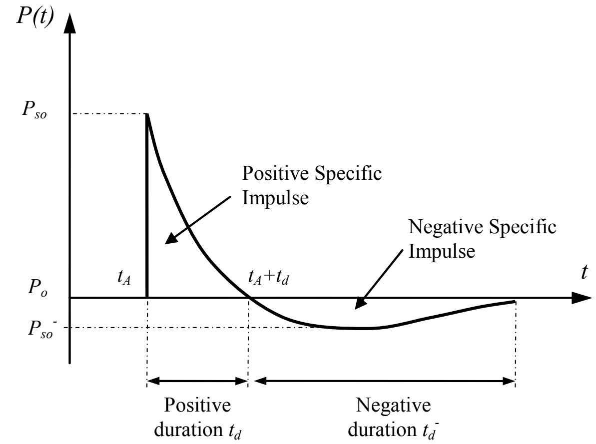


Figure 38. Blast wave pressure - Time history (Ngo et al. 2007).

However a surface burst explosion occurs when the detonation occurs close to or on the ground surface. The initial shock wave is reflected and amplified by the ground surface to produce a reflected wave. Unlike the air burst, the reflected wave merges with the incident wave at the point of detonation and forms a single wave. In the majority of cases, terrorist activity occurs in built-up areas of cities, where devices are placed on or very near the ground surface.

When an explosion occurs within a building, the pressures associated with the initial shock front will be high and therefore will be amplified by their reflections within the building. This type of explosion is called a confined explosion. In addition and depending on the degree of confinement, the effects of the high temperatures and accumulation of gaseous products produced by the chemical reaction involved in the explosion will cause additional pressures and increase the load duration with in the structure. Depending on the extent of venting, various types of confined explosions are possible.

When a condensed high explosive is initiated the following secuence of events occurs. Firstly, the explosion reaction generates hot gas which is at pressure from 100 up to 300 kilobar and at a temperature of about 3000-4000oC. A violent expansion of the gas then occurs and the surrounding air is forced out of the volume it occupies. As a consequence a layer of compressed air- the blast wave- forms in front of this gas containing most of the energy released by the explosion.As the gas expands its pressure falls to atmospheric pressure as the blast wave moves outwards from the source. The pressure of the compressed air at the blast wavefront also falls with increasing distance. Eventually as the gas continues to expand it cools and its pressure falls a little below atmospheric pressure. This "overexpansion " is associated with the momentum of the gas molecules. The result of overexpansion is a reversal flow towards the source driven by the small pressure differential between atmospheric condition and pressure of the gas. The effect on the blast wave shape is to induce a region of "underpressure" which is the "negative" phase of the blast wave. Eventually the situation returns to equilibrium as the motions of the air and gas pushed away from the source cease(Mays & Smith 1995).

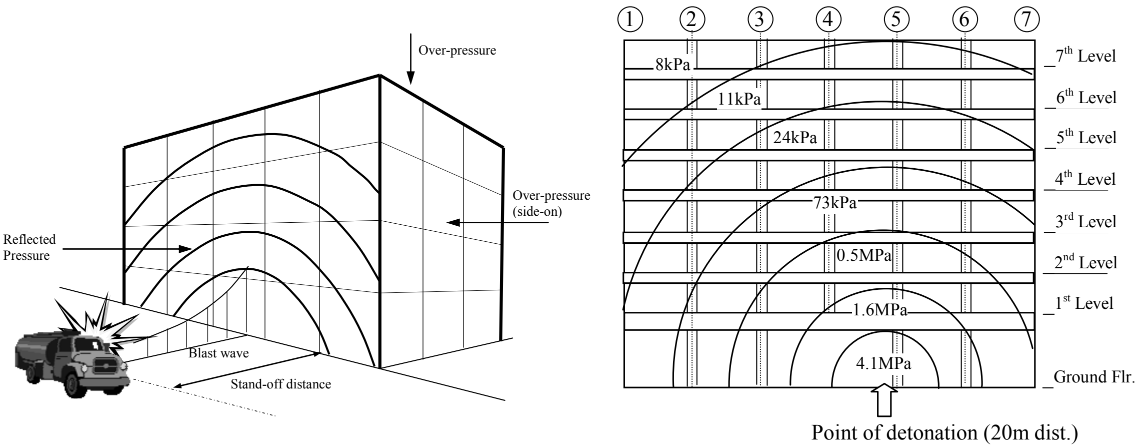


Figure 39. (left) Blast loads on a building, (right) distribution of blast pressure on building facade (Ngo et al. 2007).

External blast loading on structures

Three classes of blast wave-structure interaction can be identified.

The first of these is associated with a large-scale blast wave. In this case the target structure in engulfed and crushed by the blast wave. There will also be a translational force tending to move the whole structure laterally but because of the size of the structure it is unlikely to be actually moved.

The second category is where a large-scale blast wave interacts with a small structure like a vehicle. The target will be again engulfed and crushed, with a more or less equal squashing overpressure acting on all parts of the target at the same time. The translational force will be sufficient in this case to move the target and a substantial part of the resulting damage will be as a consequence of this motion.

The third category is associated with a blast wave produced by the detonation of a relatively small charge loading a substantial structure. Here the loading experienced by, and the response of, individual elements needs to be analysed separately since the components are likely to be loaded sequentially.

The following figure is useful in uderstanding the blast wave loading on a structure. The diffraction of the blast around the structure will engulf the target and cause a normal squashing force on every exposed surface. The structure experiences a push to the right as the left-handed side of the structure is loaded, followed shortly by slightly lower intensity push to the left as diffraction is completed. The drag loading component causes a push on the left side of the structure followed by a suction force on the right hand side also acting to the right as the blast wave dynamic pressure passes over and around the structure.

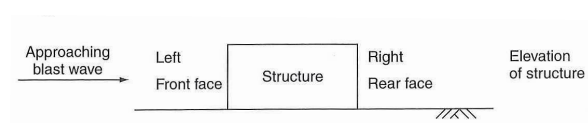


Figure 40. Blast loading on structures

Figure 40 illustrates the effects on a number of targets subjected to a blast wave produced by the detonation of a large quantity of a high explosive at large stand-off, such that the duration of the wave is sufficient to be sustained for long enough to set objects in motion.

Figure 41 (a) shows a house, a tree and a dog prior to the arrival of the blast wave. Figure 41 (b) shows the targets responding just after the blast wave front has passed. The house and the tree are engulfed by the process of diffraction, all exposed surfaces experience some level of loading. Weak elements of the building, like the glazing fail. However, the whole house and the tree, both fixed to the ground, do not move. The dog on the other hand responds differently. Through being squashed by the waves, it is being carried along by the "blast wind". At the same time, objects not firmly fixed to the house and the tree such as roof tiles and leaves are also ripped off. Figure 41 (c) shows the situation once the positive phase is over. In Figure 41 (d) the targets are experiencing the negative phase, which is associated with rarefaction and a flow of air back towards the point of detonation. Figure 41 (e) show the final situation, after the blast has entirely ended with an array of damaged objects.

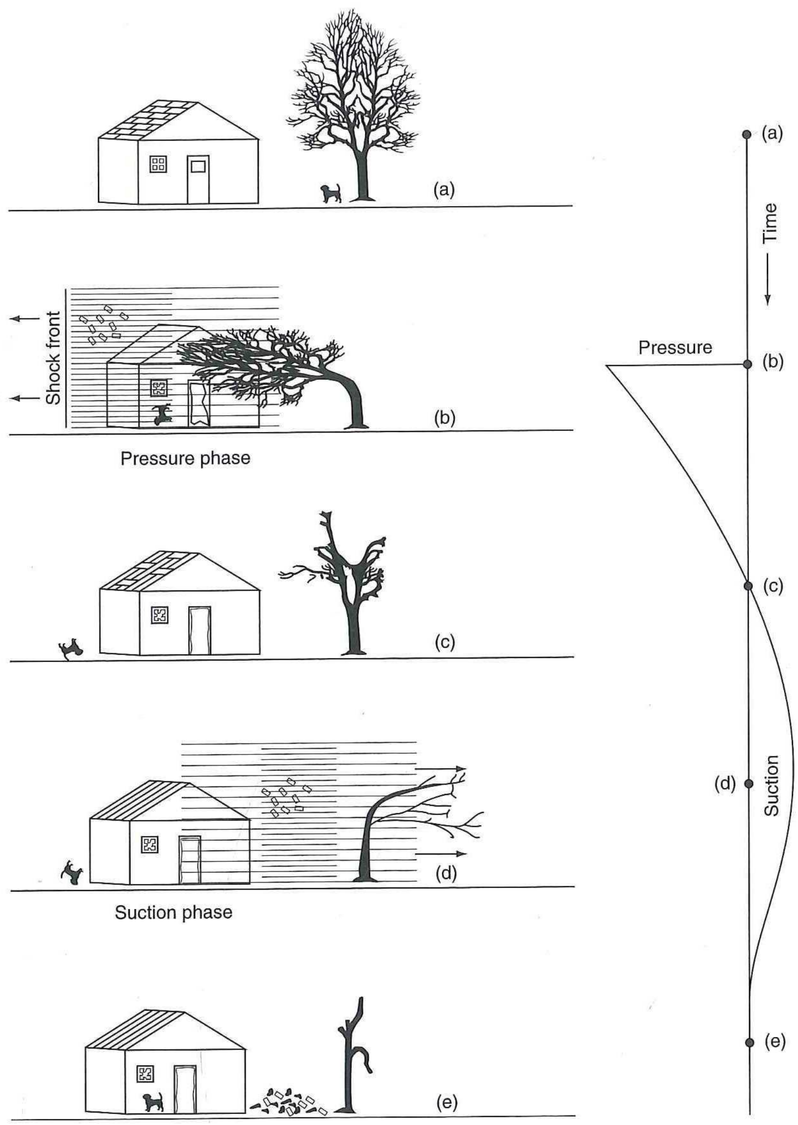


Figure 41. House, tree and dog subjected to blast loading

8.3. Principles of blast design

The front face of a building experiences peak overpressures due to reflection of an external blast wave. Once the initial blast wave has passed the reflected surface of the building, the peak overpressure decays to zero. As the sides and the top faces of the building are exposed to overpressures (which has no reflections and are lower than the reflected overpressures on the front face), a relieving effect of blast overpressure is experienced on the front face. The rear of the structure experiences no pressure until the blast wave has travelled the length of the structure and a compression wave has begun to move towards the centre of the rear face. Therefore the pressure built up is not instantaneous. On the other hand, there will be a time lag in the development of pressures and loads on the front and back faces. This time lag causes translational forces to act on the building in the direction of the blast wave (Mays & Smith 1995).

Blast loadings are extra ordinary load cases; however, during structural design, this effect should be taken into account with other loads by an adequate ratio. Similar to the static loaded case design, blast resistant dynamic design also uses the limit state design techniques which are collapse limit design and functionality limit design. In collapse limit design the target is to provide enough ductility to the building so that the explosion energy is distributed to the structure without overall collapse. For collapse limit design the behaviour of structural member connections is crucial. In the case of an explosion, significant translational movement and moment occur and the loads involved should be transferred from the beams to columns. The structure doesn't collapse after the explosion however it cannot function anymore.

Functionality limit design requires the building to continue functionality after a possible explosion occurred. Only non-structural members like windows or cladding may need maintenance after an explosion so that they should be designed ductile enough.

When the positive phase of the shock wave is shorter than the natural vibration period of the structure, the explosion effect vanishes before the structure responds. This kind of blast loading is defined as "impulsive loading". If the positive phase is longer than the natural vibration period of the structure, the load can be assumed constant when the structure has maximum deformation. This maximum deformation is a function of the blast loading and the structural rigidity. This kind of blast loading is defined as "quasi -static loading". Finally, if the positive phase duration is similar to the natural vibration period of the structure, the behaviour of the structure becomes quite complicated. This case can be defined as "dynamic loading".

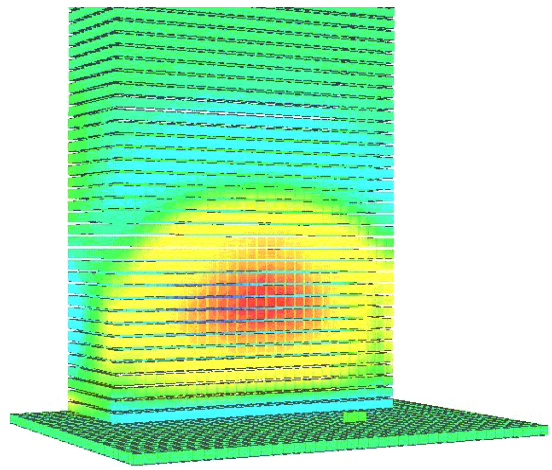


Figure 42. CFD Modelling of blast pressure on building structures (Ngo et al. 2007).

Design of glazing

The potential hazards from glazing in an explosion are obvious. Monolithic glass as a brittle material, fails suddenly and fragments. However with proper design, laminated glass can respond in a ductile manner.

The priority in the design of glazing against blast should be the safety of building occupants and therefore the avoidance of the generation of glazing fragments. Properly designed glazing can also eliminate or reduce the blast pressures which enter the building interior, either by remaining unbreached or by delaying the onset of breaching.

Different levels of facade performance can be distinguished. Firstly complete and catastrophic internal devastation to the building interior. Secondly violent inward projection of glass fragments and t penetration of blast pressures. Another level is of course the protection of the interior from the blast pressures with the laminated glass panes pulled out of their frames with small internal damage. The highest level of performance is the one offering complete protection from the blast with the glass retained in the frames.

Whole building response to blast damage

According to UK Building Regulations: "The building shall be constructed so that in the event of an accident the building will not suffer collapse to an extent disproportionate to the cause".

The first step in designing for blast is to decide what the maximum threat on the building will be during the life of the building. It is vital to determine the potential danger and the extent of this danger.

The nature of the building must be evaluated, bearing in mind all factors, including its function, any symbolic importance and its location. This last aspect is crucial: the building itself may not be a target but its overall environment might be, or it might be close to another building which could be a target (Sakula 2010).

It is important to differentiate between disproportionate and progressive collapse. A disproportionate collapse is one whose extent is greater than certain limits which are defined as tolerable. In this definition the severity of the initiating event should be recognised. A progressive collapse is one in which successive alternate loadpaths are overloaded and fail. The initiating event causes the load to be shed through alternate loadpaths.

A number of risk factors should be taken into account in defining the tolerability of risk of disproportionate collapse. Some of the most important are: population, occupancy profile, evacuation time, purpose of the building, societal expectations, form of construction, protection from threats, new/existing construction and procurement.

Having established the threat it is vital to determine the appropriate damage levels which are permissible. Most importantly human safety should be provided. Avoidance of injury to people, or loss of life, will be the primary considerations, and also damage to equipment and the building itself will be important. Complete protection under all conditions will not be achievable but there are realistic criteria which can be set in each case (Sakula 2010).

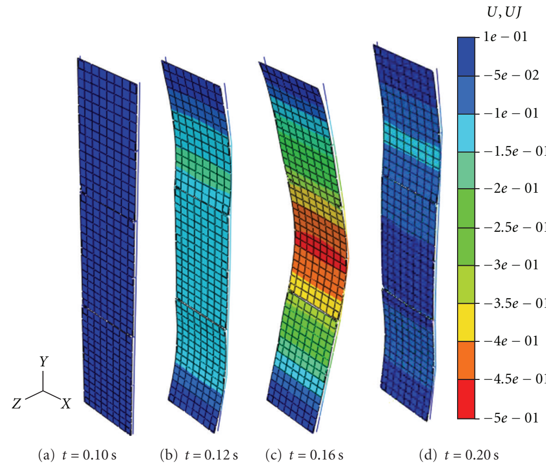


Figure 43. Typical deformed configurations of the facade module due to high level explosion (Ngo et al. 2007).

As far as injury to occupants is concerned, the main threat is flying glass due to broken windows. The appropriate level of acceptable injury is a matter for judgment and must be made with the full participation of the client and the security adviser. Typical examples are the "breaksafe" category, a stringent standard which restricts any glass fragments inside the building to within 1m of the window and the "low hazard" category, which allows glass further into the building but at 3m from the window the fragments must not be higher than 0.5m above the floor.

Methods of design

Tie force-based design methods: Rule-based approaches by which the structure satisfies robustness requirements through minimum levels of ductility, continuity and tying.

Alternate loadpath methods: Quantitative approaches whereby the structure is shown to possess adequate robustness against collapse to satisfy the code requirements. Alternate loadpath analysis necessitates an assessment of the capacity of a structure to dissipate the energy of collapse. This energy is dissipated through plastic strain which is developed by by rotation of the connections. This is the reason why the behaviour of the connections in the structural frame is of crucial importance in quantifying the capacity of the structure to resist a progressive collapse.

Types of glazing and behaviour under blast loading

- Annealed glass

Annealed glass is the common basic glazing material. It exhibits brittle fracture and high variability in strength and random crack propagation. The failure of annealed glass under a blast load usually results in a sudden and immediately high hazard to building occupants.

- Toughened glass

Toughened glass is obtained by reheating annealed glass to a plastic state, followed by controlled cooling. This process increases the effective strength of toughened glass four to six times compared to annealed glass. The failure under blast load is however brittle, although the "dice" are actually blunt-edged.

- Laminated glass

Laminated glass is a built-up composite of alterating layers of glass and interlayer. The interlayer material used for blast resistance is polyvinyl butyral (pvb), a highly ductile material, which has excellent bonding properties to glass. Upon cracking the glass fragments remain bonded to the plastic interlayer. The performance of laminated glass under blast load is significantly superior to both annealed and toughened glass in the following aspects:

1. The excellent bond between glass and pvb which remains active after the glass cracks

2. The large strain energy capacity of the pane after the glass piles have cracked

3. A ductile failure mechanism in which highly hazardous conditions do not immediately occur when the pvb reaches its limit of tearing

4. An in-built resistance to physical attack

- Framing systems

The selection of the lass type must be of course supplemented by appropriate selection and design of framing members

- Two-way spanning glass

In two-way spanning glass framing systems the pane can generate its greatest strength due to the stress system which is set up in the glass, comprising in-plane compression stresses balanced by radial tensile stresses and flexural bending stresses prior to cracking. After it cracks a laminated glass pane behaves as a flexible membrane supported on all four sides.

- One-way spanning glass

The glass is supported on two parallel edges. A one-way spanning system does not enable the development of in-plane compressive stresses in the pane before it cracks. After cracking, laminated glass again behaves as a membrane although it has greater flexibility than the two-way spanning pane. The resistance will therefore be lower.

- Bolt-fixed glass

The panes are supported by bolts through holes in the glass at each corner of the pane and possibly intermediate points. The bolts carry the pane loads to a secondary skeletal structure. The blast load resistance exhibited by bolt-fixed glass is low compared with that provided by the same glass in a four-sided frame. However the substantial thickness often provided will give reasonable resistance until cracking is initiated.

- Elastomeric gaskets

Elastomeric gasket strips provide edge retention. It is a quick and cheap solution, but laminated glass will not be able to develop its full membrane tearing strength. Thicker laminates are only partially held before their pull-out forces overcome the friction offered by the gaskets.

- Structural silicone

Effective edge restraint of glass to resist in-plane forces is most effectively provided by structural silicone. It allows shear stresses to be transferred between the glass and the framing member. Structural silicone glazing allows much greater blast loads resistance than the elastomeric gaskets.

Design of laminated glass for blast loads

The objective is to provide sufficient pre-crack resistance and post-crack membrane capacity in the glazing design such that the work done by the applied blast load may be resisted by the strain energy developed by the pane, and so that the pane remains within its limit of tearing and excludes blast pressures from the building interior. The blast load may be idealised as a triangular pressure-time function with zero rise time. Unlike the design of structural steel and reinforced concrete which is based on response charts, the glazing design generally requires a time history analysis using a single degree of freedom (SDOF) theory because of the more complicated resistance-displacement function.

Key element design: Last resort method, a quantitative design approach for designing elements, the removal of which would lead to a collapse defined as disproportionate.

8.4. Discussion

Blast loads are unpredictable, instantaneous and extreme. Therefore, it is obvious that a building will receive less damage with a selected safety level and a blast resistant architectural design. On the other hand, in order a building to be entirely "blast proof" extreme measure need to be taken. The outcome would be a building with small windows that is directly in opposition to the latest trend which is to maximize natural lighting and to make use of solar gain (Sakula 2010).

The challenge for building designers in general and façade engineers in particular, is to provide clients with informed and balanced advice on the appropriate level of protection without creating a world of fortress buildings (Sakula 2010).

Blast resistant building design method usually conflicts with aesthetical concerns. For example foyer areas are the most vulnerable areas and according to this design method it is suggested that Foyer areas should be protected with reinforced concrete walls and the entrance to the building should be separated from other parts of the building by robust construction for greater physical protection. That is in contrast with the architects wish that envisions these areas as open and welcoming to the public.

The motive of this research is to suggest a solution to this problem providing a blast resisting structure but at the same time minimal according to the architectural trend of the times.

In total it is important to recognise that there is no universal approach to designing for robustness. It should also be noted that the thresholds given in national guidelines of the level of damage which is considered disproportionate are for accidental actions rather than for those of malicious origin.

Once the engineer has arrived at a design basis for robustness in the design of a building, the next task is demonstrating compliance with it. The methods for this vary and it should be also pointed out that there is a shortage of data on connection ductility capacities, especially in relation to the combined influence of rotational and axial connection deformations.

9. Existing cable net facades

The early design of the cable net facade was performed by Schlaich and Schobe and it was first built for the Kempinski Hotel at the Munich Airport in Munich, Germany, in 1989. Subsequently, cable net façades were duplicated worldwide because of their high transparency and geometric flexibility (Teich et al. 2011).

Compared to the traditional hyperbolic cable net, cable net facade is a plane structure that does not have a negative Gauss curvature and thus has a relatively weak stiffness in the direction that is perpendicular to the plane of the cable net. The permissible deflection of the cable net facade is normally 1/50 of the span, but for some special cases it may be 1/40 of the span. This indicates that it is important to consider the geometric non-linearity in the analyses. This feature also highlights the difference in performance between cable net facades and the other cable net structures (Feng et al. 2008).

Design and configuration

The typical configuration of a cable net facade is shown schematically in Fig. 1. The main construction element is a net of prestressed steel cables. The frame construction has to provide sufficient stiffness to resist the cable forces. For cable net facades with an aspect ratio (width/height) greater than 2, the loads are mainly carried in the vertical direction (Schlaich et al. 2005). Consequently, the prestress forces of the vertical cables are much greater than the prestress forces of the horizontal cables. Especially in the early design stage, the influence of the horizontal cables is neglected, and the external loads are assigned to the vertical cables. The horizontal and vertical cables are linked at their intersections (Teich et al. 2011).

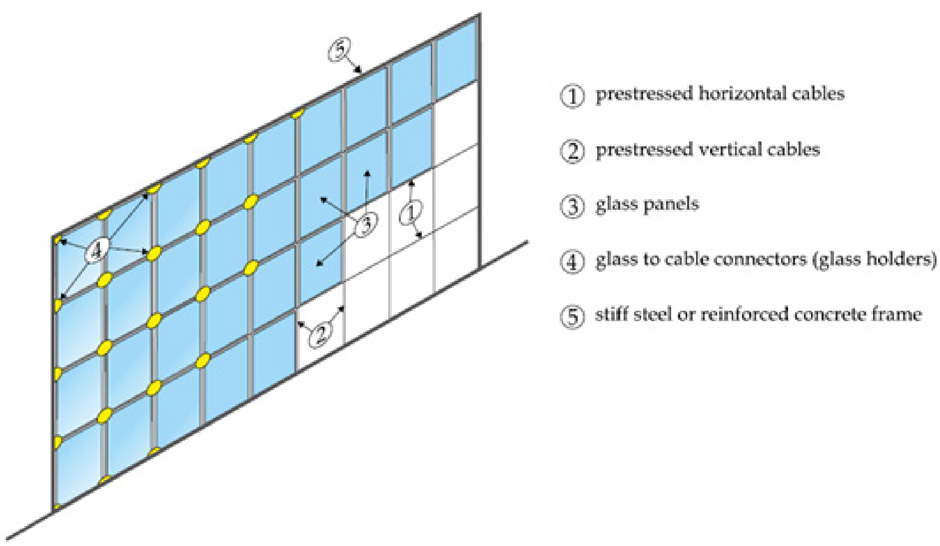


Figure 44. Typical configuration of cable net facade (Teich et al. 2011)

The glass holders link the steel cables and connect the corners of the glass panes to the cable net. Laminated safety glass is used and two types of glass holders are the most common; drilled glass bolt fittings and patch plates. Usually one front and one back plate clamp four glass panes to one node while accommodating the deflections and rotations of the glass panes. These holders must also retain the glass panes while the facade deals with large deformations.

The prestress level of the cables is determined by the maximum permissible deflections under the design loads. The cross-sections of the steel cables are in their turn determined by the required load capacity and the prestress level. The thickness of the glass also depends on the design loads and is usually between 6 and 10 mm per glass layer.

Structural Behaviour

Cables carry loads by axial forces, but provide almost negligible bending stiffness. The general behaviour of the cable net facade is characterised as flexible and highly non-linear. The eigenfrequencies of cable net façades are usually small and depend on geometry, prestress level, and cable diameter. Typical permissible in-service deflection limits are in the range of 1/40 to 1/50 of the shortest facade span (Feng et al. 2009; Ruoqiang et al. 2006) and adjusted by axial cable stiffness and cable prestressing. These deflection limits generally guarantee the integrity of the glass panes. In extreme loading conditions, like the blast loading case, these limits can be greater but the need of detailed studies to determine these limits is real. In any case it is impossible to use safety standards corresponding to stiff protective structures, since cable net façades behave in a non-linear way and are capable of large deflections.

While flexible systems usually are not designed to withstand strong blast loads, they should offer protection against low-level blast loads (Amadio & Bedon 2012). Cable net façades can achieve better blast-proof performance with large deformations and large support rotations, but a special design and analysis is required. The study of the dynamic response of the cable net systems is becoming lately popular and focuses on avoiding injuries and minimising structural damage. They should be able to resist the incoming blast wave and dissipate as much energy as possible.

Figure 45. Cable net facade Leipzig Main Station (Teich et al. 2011)

III. Design

Overview of the design strategy and the structural principles.

10. Design strategy

10.1. Form Simulation

In the beginning a parametric model using Grasshoper was made. The aim was to represent a simplified version of the form of a spiderweb. The basic assumptions were the full symmetry of the web in both axes and shape of spirals as perfect circle. Initially the given parameters were the length of the radius, the number of radii and the number of spirals (Figure 47).

In the next phase the plug-in Kangaroo (a Live Physics engine for interactive simulation, optimization and form-finding directly within Grasshopper) was used in order to give to the structure physical characteristics and transform the group of lines to a system with the properties of a cable net. Kangaroo makes use of a particle-spring system in which particles are connected using damped springs creating a network that represent the cable net.

The initia

Set-up of the model

The Spider web model was created as a set of lines grouped in radial and tangential direction. In order to ensure that all cables behave as (perfect) cables each line is split in exactly in the middle. Springs are presented as lines. The connecting node between the two elements acts as a hinged connection and thus ensures that only axial tension loads can be transferred by the element Figure 46 and Figure 48.

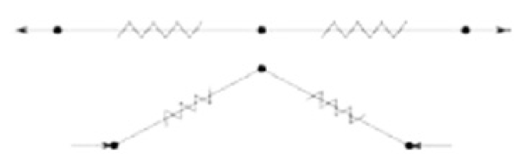


Figure 46. Spring that resists to extension, but not to compression (Eigenraam 2013)

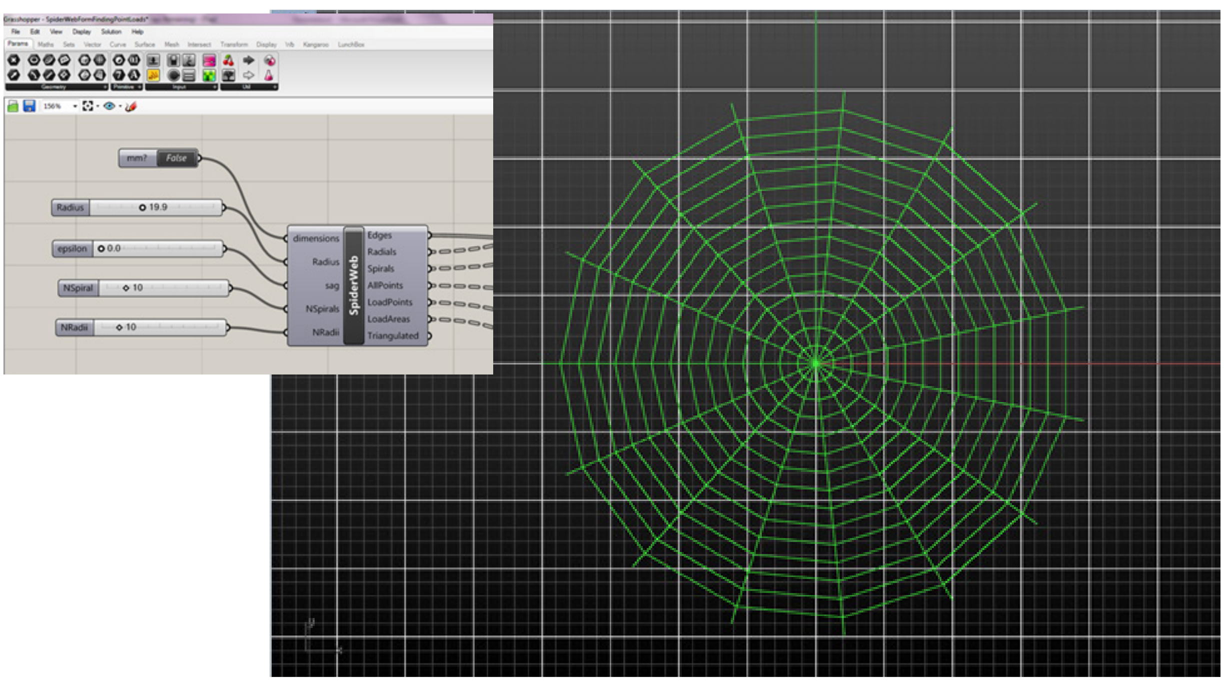


Figure 47. (left) Cluster component in Grasshopper parametric modelling environment, the input 'sliders' represent the parameters of the model, (right) the geometric expression in the Rhinoceros viewport

Interpretation of Kangaroo geometry

All elements are modelled as Kangaroo spring components. At first the rest length is taken as the length of the input lines (i.e. the cable structure without any external forces acting on it is in rest at t=0).

Alternatively the rest length can be shortened as a proportional to the input length of the lines (factor between 0 and 1). In this way the cable structure will have an initial internal force at t=0, and they can act as pre-stressed elements.

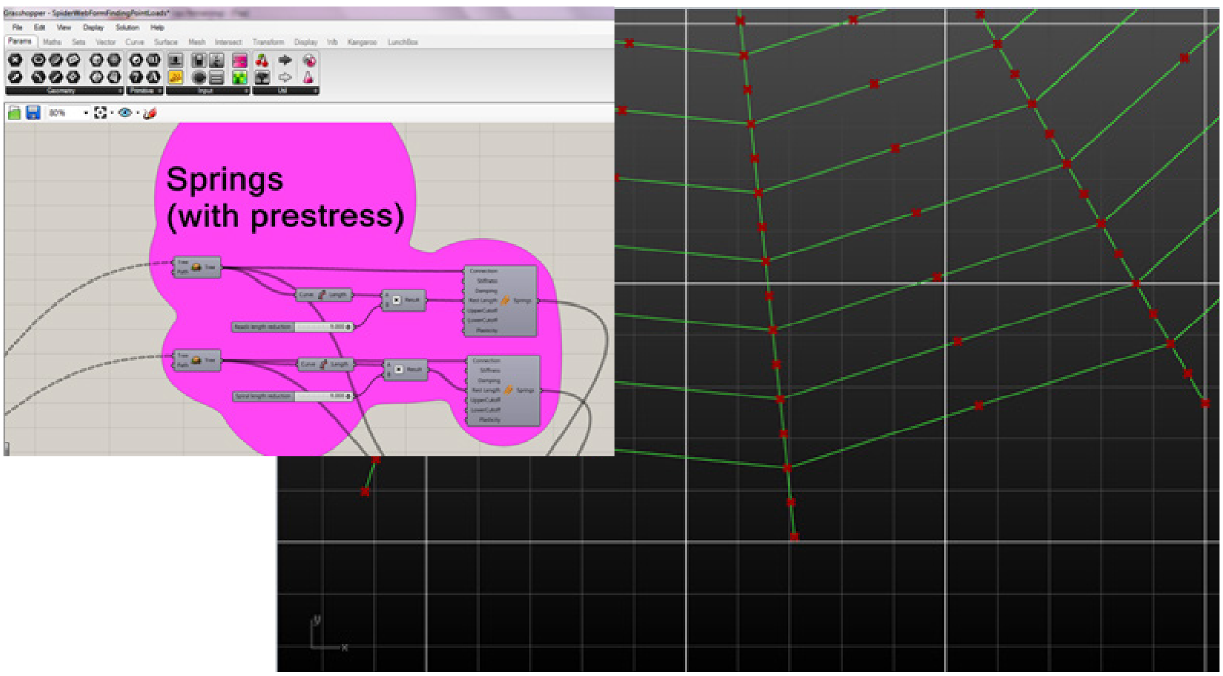


Figure 48. Interpretation of Grasshopper geometry into Kangaroo physics objects, the cables are modelled as springs and divided in the middle by a hinged connection which ensures that only axial tension loads can be transferred by the element

Interpretation of Kangaroo loading

Kangaroo uses “Particles” as fictive objects with mass and position, velocity. They can respond to forces but have they have no spatial dimension. Therefore Forces should be applied on these particles.

Newton’s second law states that an object, here the particle, will accelerate proportionally to the direction and magnitude of an applied force. When a force is applied to a particle it will move due to the acceleration. A new position can be calculated within a curtain time step. The particles move relative to each other and thereby the springs are stretched or compressed. Hence, the springs apply a force to the particles. This changes the sum of forces acting on a particle. In the next time step a new position can be calculated using the new direction and magnitude of the sum of forces. Damping is applied to the springs so that after many time steps the particles come to a standstill. Without damping the spring network will continue to move. More details on particle springs systems can be found at (Kilian & Ochsendord 2005).

In the basic model only point loads on the nodes of the model are given. These point loads are derived from the area around the node assigned to that specific node.

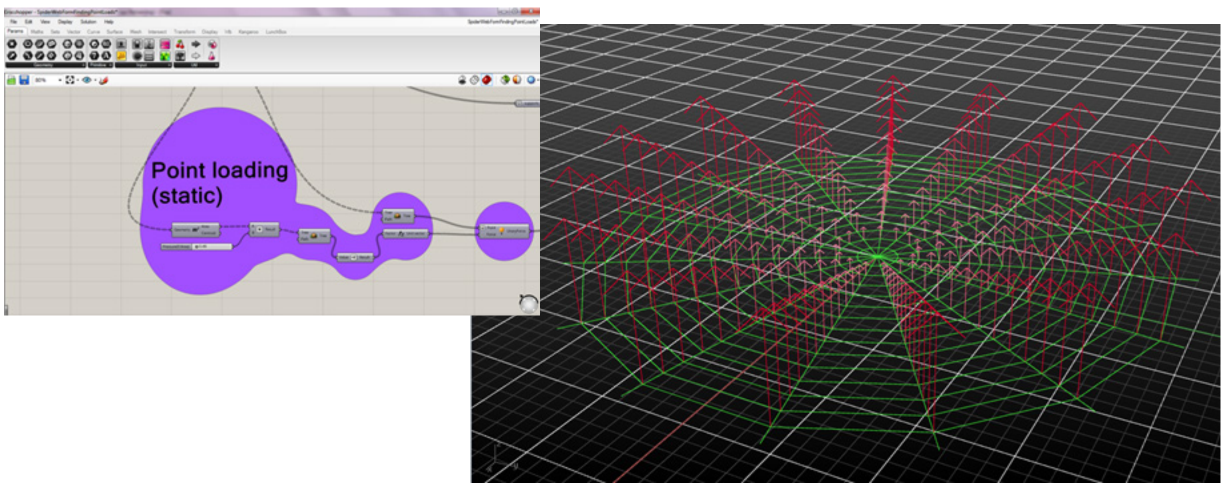


Figure 49. Visual representation of the load vectors proportional to the load distribution area of the glass panes

Deformed shape

The add-on is capable of simulating the motion of this digital representation of a cable net in a spider web form. Fig. shows the deformed shape.

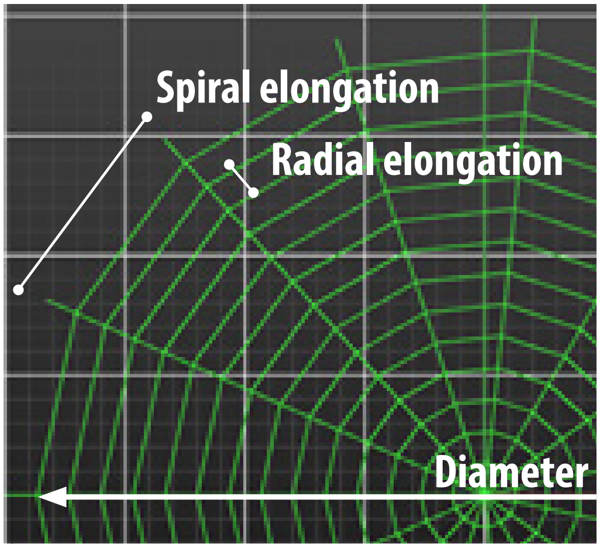
It should be noted that although it is not an exact simulation of a cable net, it is a good approximation of the structural response of a cable net in a shape of spider web and the result is comparable to the one of a nature spider web.

Modeling of glass panes

Before starting with the detailing of the glass connection, we modelled the glass panes.

Restricted the maximum deformation to 1.5m, with the same dimensions but with only with 10 radii and 9 spirals we noticed that distances both between radii and spiral are getting bigger as the web deforms.

Therefore, it was evident that a connection, that could supportthe glass while the radii and spirals moving away, was necessary. Dimensions and design derived as a consequence from these results.



radials (m)	spirals (m)	diameter (m)
0.0354	0.0049	0.0316
0.0245	0.0070	0.0445
0.0164	0.0072	0.0460
0.0107	0.0065	0.0412
0.0070	0.0053	0.0336
0.0047	0.0040	0.0254
0.0035	0.0028	0.0177
0.0029	0.0017	0.0110
	0.0008	0.0052

Figure 50. Overview of geometric elongation of web elements (from outside to inside)

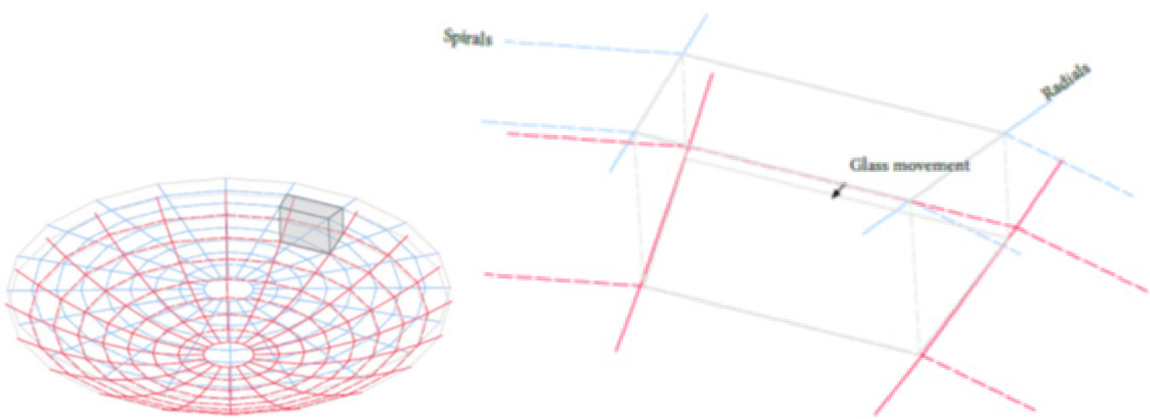


Figure 51. Movement of the glass panes in the deformed state.

Conclusions

The initial purpose for the use of Kangaroo was to investigate possible stable forms for the spider web under dynamic loading (blast loading in the specific case). Having established a stable shape (under these loads) the analysis of the structure would be possible with the use of Finite element software.

Unfortunately, form finding analysis under dynamic load was not possible but the model provided us with a better understanding about the way that this net deforms. This understanding was valuable for the design of the connection detailing, as the previous paragraph "Modelling of glass panes" explicitly explains.

10.2. Analysis approach

Blast scenario and design assumptions

For the purpose of this thesis and regarding the characteristics of the specific case study, in order to start making basic calculations and model the structure, we determined the blast scenario the following blast scenario.

The explosion will be a chemical and the type of explosive will be condensed. Specifically, a track full of TNT stops close to Markthall. Since all the existing information is in respect to the TNT explosives, this choice seemed rather obligatory. The stand-off distance was derived from the distance between the building and the accessible roads by truck in combination with the GSA code and it defined as 35m. All the details regarding the blast wave parameters are presented in the paragraph 10.3 Hand calculations.

Based on that, a simplification was made for the distribution of the blast load on the façade. Since the blast wave propagates in milliseconds, it is assumed that the distance is long enough so as the load could be considered uniformly distributed on the façade, for the purpose of the hand calculations and for the conceptual design.

Finally, it should be noted that the calculations and the concept design are applicable to this specific design scenario and specifically for the positive phase of the blast phenomenon. However, with further development we are confident that the system could also work adequately for the negative phase.

Explosion in the interior of the building is out of the scope of this research.

Quasi-static approach

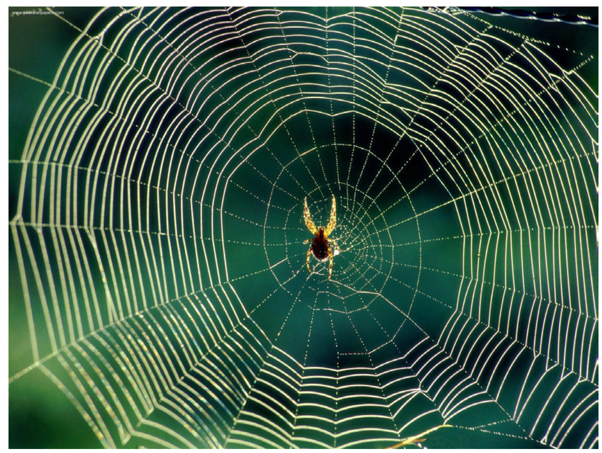
In assessing the behaviour of the blast-load structure it was the case that the calculation of final stages was the principal requirement rather than a detailed knowledge of its displacement-time history. The feasibility of the structural system was dependent on this information.

To establish the principles of this analysis, the response of a single degree of freedom (SDOF) elastic structure was considered and the link between the duration of the blast load and the natural period of vibration of the structure established.

The principles of analysis for a SDOF system are extended to specific structural elements which can then be converted back to equivalent lumped mass structures by means of load and mass factors. Total structural resistance can thus be represented by the sum of an inertial term (based on the mass of the structure) and the so-called "resistance function" (based on the structure's geometrical and material properties) which act in opposition to the applied blast (Mays & Smith 1995).

FEM approach

Although spiders have made spider webs for millions of years, predictive modelling is difficult.



A real spider web is composed of a series of strong connected fibres. Impact on the web stretches the fibres. Thus the elasticity of the fibre material provides an energy dampening effect. Important to realize is that in actual usage only the weight of the spider loads the web. As the web is an open space the wind load is negligible. The moving spider slightly distorts the web but does not load it significantly. Only the impact of a large prey on the web causes considerable deformation. The energy of the impact is absorbed by hyper elastic deformation of the spider silk fibres.

The energy absorbing behaviour of spider webs has led to research into using spider silk into bulletproof vests and spider web structures in blast resistant façades.

To understand blast resistant spider web façades finite element modelling needs to be developed as a design tool. No literature or examples about this are known. Paragraph 10.4 Computational FEM analysis, deals with the modelling issues.

10.3. Quasi static analysis-Hand calculations

	Notations
E	*Young's modulus of elasticity (table)*
F	*Peak blast load of idealized triangular pulse*
F(t)	*blast load from idealized triangular pulse*
I	*impulse*
K	*stiffness*
k*	*equivalent stiffness*
KE	*kinetic energy*
M	*structure mass*
m*	*equivalent mass*
p_r	*peak reflected pressure*
P	*blast load*
P*	*equivalent blast load*
R	*range, structure resistance, static load to cause same deflection as blast load*
t_d	*duration of idealized triangular blast load*
t_m	*time to reach maximum dynamic displacement*
U	*strain energy*
u_{max}	*maximum displacement*
WD	*work done by the blast load*
x	*displacement*
x_{max}	*maximum dynamic displacement*

Lumped mass equivalent SDOF systems

To aid assessment of response, the behaviour of complex structures can be approached by representing the structure as a SDOF lumped-mass system- the so-called equivalent system.

The structure is subjected to a blast load idealized as a triangular pressure-time function with zero rise as shown in Figure 54. The positive phase duration of the blast load is t_d. In the impulsive regime, the duration of the applied load, td, is short in relation to the response time, t_m, of the element (the time for the element to attain a deflection X_m), such that $t_m/t_d > 3$. The loading is assumed to be uniformly distributed and is represented by the specific impulse I given by the equation $I=1/2*p_r*t_d$, the area beneath the load function 0<t<td (Mays & Smith 1995).

In creating an equivalent SDOF structure it must be realized that real structures are multi degree of freedom systems where every mass particle has its own equation of motion. Thus, to simplify the situation it is necessary to make assumptions about response and particular characterize deformation in terms of single point displacement.

The equivalent system is presented in Figure 52 where the suffix * means equivalent.

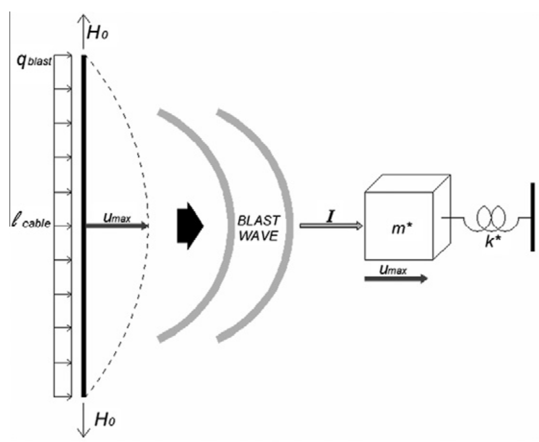


Figure 52. Simplified approach for approximate analysis of the façade-module subjected to air blast loading (Amadio & Bedon 2012)

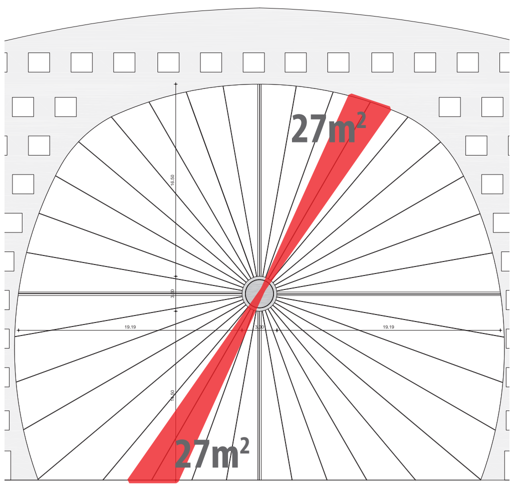
This method relies on considering the energies of the real structure and the equivalent system and equating them. This means that, by ensuring equal displacements and velocities in the two systems, kinematic similarity is maintained. The complete energy relationship may be written as:

$$WD = U + KE$$

	Modulus of elasticity (N/m^2)	Poisson's ratio (–)	Density (kg/m^3)	Behavior (–)
Glass panes	7×10^{10}	0.23	2490	Linear elastic
PVB-film	5×10^{8}	0.50	1100	Elastoplastic
Harmonic steel (cables)	1.3×10^{11}	0.32	7300	Linear elastic
Stainless steel (spider devices)	2.1×10^{11}	0.32	7300	Linear elastic

Figure 53. Table expressing the material properties of the facade component

Description of the specific cable-supported glazing system



The facade front view is illustrated above. Each laminated glass panel has a total nominal thickness t = 24.5 mm, which is obtained by assembling two fully tempered glass sheets ($t_1 = t_2 = 10$ mm) and a middle PVB-interlayer (tPVB = 4.5 mm). Radial φ = 36 mm diameter steel cables are subjected to an initial pretension Ho = 300 kN.

Please note that in the initial stage -prior to any analysis- the values were based on thumb rules assumptions and therefore they are not in agreement with the dimensioning of the final conceptual design.

Mass calculation

We assume a perfect circle with diameter=d=35m (Radius R=17,5m) and number of radii n= 18.

The total façade area is:

$$A_{tot} = \pi R^2 = 962 m^2$$

Therefore the glass area that corresponds to each cable is:

$$A_c = A_{tot}/n = 54\ m^2$$

Weight of one glass pane:

$$54m^2 * 2490\ kg/m^3 * 10 * 10^{-3} = 1345\ kg$$

$$PVB: 54m^2 * 1100\ kg/m^3 * 4{,}5 * 10^{-3} = 267{,}3\ kg$$

Total mass:

$$M = 2956{,}3\ kg$$

Blast load definition

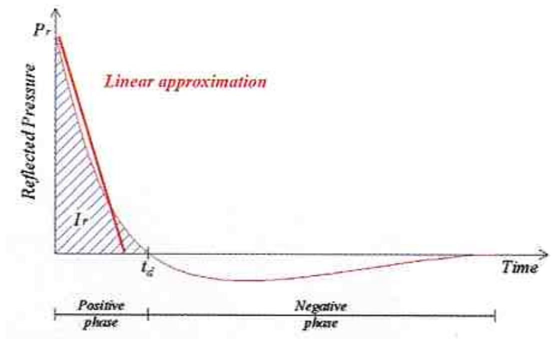


Figure 54. Blast load time-varying pressure function over time (Wellershoff 2011).

In the specific circumstance, according to the GSA document (Level D of GSA Figure 55) the time-varying pressure function is described in the form of a triangular pulse which instantaneously reaches its maximum value (static overpressure peak $p_r = 68.9$ kPa) and decays linearly to zero pressure at 0.02s. The level D blast load was applied to the glass surface in the form a uniformly distributed, impulsive load qblast representative of the positive phase of the time-pressure function.

Considering the equivalent system as shown in Figure 52 , it is necessary to assume that the cable could deform only in a single shape (e.g. a parabolic shape) under a uniformly distributed static load. The evaluation of the work done, strain energy and kinetic energy for the beam is then made. The equivalent system will have the same maximum displacement u_{max} and maximum initial velocity (v) as for the real structure (Amadio & Bedon 2011).

Class	Pr [kPa]	Ir [kPa ms]	td [ms]	TNT [kg]	Stand off [m]
GSA C	27,58	193,06	14,0	47,5	30
GSA D	68,95	675,71	19,6	340	34

Figure 55. US blast load assumptions (Wellershoff 2011)

Analytical procedure for estimating the response of the façade

When the air blast wave invests the façade-module, it approximately behaves as a SDOF that receives an external total impulse I. It acquires a quantity of motion Q = I = Mv and starts to oscillate with an initial velocity v , having defined M = 2956,3 Kg its total mass. After having reached the maximum deformed configuration, the SDOF partly releases the elastic energgy stored in the cables, thus it turns back toward the initial position by means of a damped oscillating motion (Amadio & Bedon 2011).

Equivalent dynamic parameters

The essential dynamic parameters of the equivalent SDOF can be reasonably determined, referring to Ritz's method, by using the classical energy approach. In this manner, the original problem is solved in a static way and the pretensioned cable of length l_{cable} is considered subjected to a uniformly distributed blast load q_{blast}.

Just before the explosion occurs, the total pretension in the cable is H = Ho. Considering the pretensioned cable having uniform properties along its length, its free vibration equation of motion is:

$$H\frac{\partial^2 u(x,t)}{\partial x^2} = \mu A_{cable}\frac{\partial^2 u(x,t)}{\partial t^2} \tag{6}$$

With μ the mass density per unit of length; A_{cable} the cross-section area of the cable; u(x, t) the transversal displacement of its generic section.

The dynamic parameters of the equivalent SDOF (mass m*, stiffness k*) can be estimated by imposing an energy balance between the MDOF and SDOF systems, that is by equalling their elastic and kinetic energies:

$$E_{cable_{elastic}} = \frac{1}{2}\int_0^{l_{cable}} Hu'dx \tag{7}$$

$$E_{cable_{kinetic}} = \frac{1}{2}\int_0^{l_{cable}} \mu A_{cable} v^2 dx \tag{8}$$

the maximum energies of the equivalent SDOF in undamped free vibrations are:

$$E_{SDOF_{elastic}} = \frac{1}{2}k^* u_{\max}^2 \tag{9}$$

$$E_{SDOF_{kinetic}} = \frac{1}{2}m^* v_{\max}^2 \tag{10}$$

with u_{max} and v_{max} its maximum displacement and velocity.

Reasonably, the equivalent mass m* and stiffness k* can be estimated by equalling the elastic (Eqs. (7) and (9)) and the kinetic (Eqs. (8) and (10)) energies of the lumped-mass and the SDOF system, resulting:

$$k^* = \frac{16H}{3l_{cable}} \tag{11}$$

$$m^* = \frac{16M}{30} \tag{12}$$

Dynamic response due to blast loading

Ignoring possible damping contributions, for the energy conservation, after the explosion has been occurred the kinetic and strain energies must be equal to the incoming energy E_{blast}, in each instant:

$$\frac{1}{2}m^* v^2 + \frac{1}{2}k^* u^2 = E_{blast} \tag{13}$$

In eqs. (9) and (10) u_{max} and v_{max} respectively denote the maximum displacement and velocity reached by the oscillating SDOF system because of explosion; m* and k* were defined by Eqs. (11) and (12); $E_{blast} = I^2/2M$. Eq. (13) can be considered the equation which governs the response of the examined equivalent SDOF system subjected to air blast loads. In the deformed configuration (maximum potential energy and zero kinetic energy), the maximum displacement of the SDOF system results:

$$u_{\max} = \sqrt{\frac{I^2}{Mk^*}} = I\sqrt{\frac{16}{30m^* k^*}} \tag{14}$$

Iterative procedure

An accurate evaluation of the equivalent stiffness *k** and therefore of the maximum displacement due to air blast loading should be developed taking into account that because of the blast explosion the initial pretension force H_0 affecting the cable increases abruptly and significantly.

Assuming for the deformed cable a parabolic shape function the increase H_{blast} of the initial pretension H_o results:

$$H_{blast} = \frac{8}{3}\frac{E_{cable}A_{cable}}{l_{cable}^{2}}u_{\max}^{2} \tag{15}$$

with E_{cable} the Young's modulus of harmonic steel constituting the cable (table in Figure 53) and u_{max} defined by (14)

Consequently, the maximum total pretension force affecting the cable after the explosion is:

$$H = H_{\max} = H_{o} + H_{blast} \tag{16}$$

To estimate u_{max} correctly, an iterative process should be performed by iteratively substituting Eq. (14) in Eq. (15) until the obtained value u_{max} remains constant.

In general, depending on the intensity of air blast, this iterative procedure rapidly converges but it is fundamental to correctly describe the maximum effects of the explosion. The results of the hand calculations are shown in Figure 56.

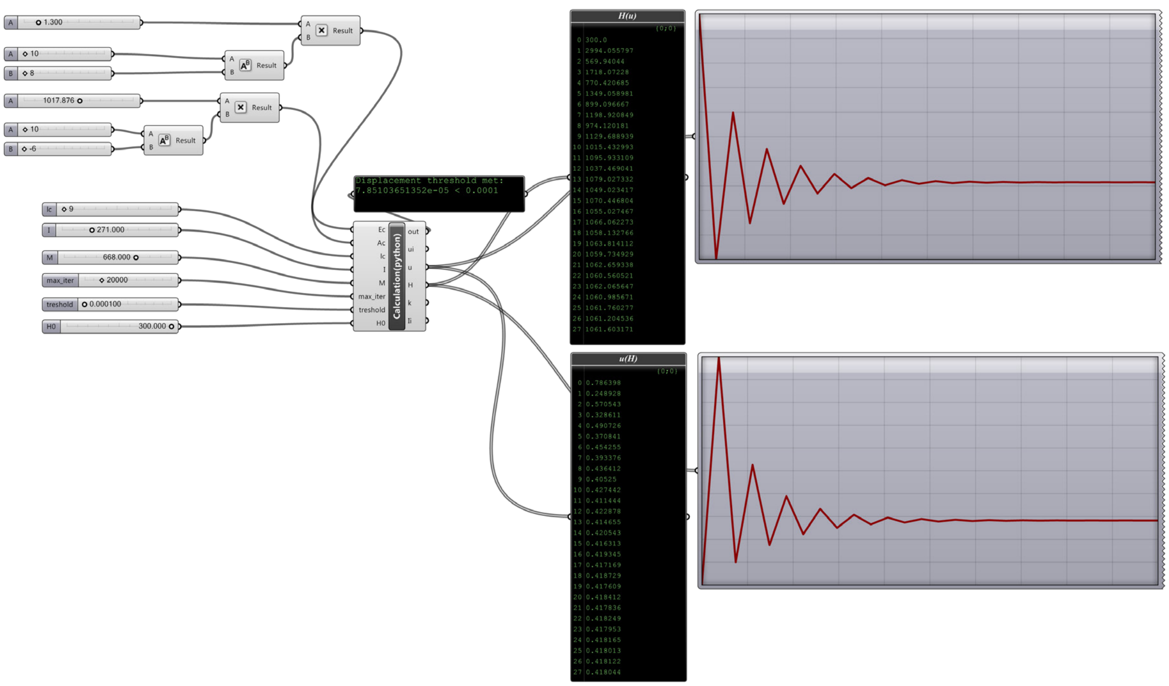


Figure 56. Scripted iterative calculation results in Grasshopper and output of maximum deformation (u) and axial force (H)

Conclusions

The values for the maximum deformation and axial forces were exceeded the maximum allowable values with a factor of 3. A max deflection approximately equal to 1/20 of the structural span is normally accepted for this type of loading (in this case about 1.75m). However, the result of about 4,60 m from the hand calculation was valuable in the initial stage be, since it confirmed the feasibility of the structure and indicated the necessity of an additional loadbearing mechanism, that could reduce the values in accrodance to the allowable. The introduction of such a mechanism is described in the next chapters.

10.4. Computational FEM analysis

Modelling

Essentially a spider web façade is a series of wires suspended from a strong and stiff surrounding element on which façade plates are hung. Implicit in this are some critical differences between the spider web façade and a spider web.

- The spider web is not rigidly suspended and has no façade plates
- The spider web façade needs to be flat in the normal mode and this implies pre-stress to tighten the cable and prevent sagging on one hand some spring and dampener system to allow the cables to stretch and deform to absorb the energy.

From a finite element modelling perspective this implies that the model is not static but transient and has large deformations of long thin structural elements.

- From a modelling perspective this requires:
- A non-linear transient analysis
- A distributed force applied on the web
- A rigid core/dampener in the centre to connect the cables
- Fixing the cables at the end
- A tension only cable element to model the web elements.
- Some way of dealing with the mass of the glass façade plates while the web is moving, assuming that the plates can slide frictionless over each other.

Some modelling was done in Diana but this was found to be complicated. The modelling effort was then switched to ANSYS which is a more flexible FEM package as it is more mechanical engineering orientated.

First model

The first model was a simple web structure of steel cables connected to a central steel core. It is illustrated in Figure 57.

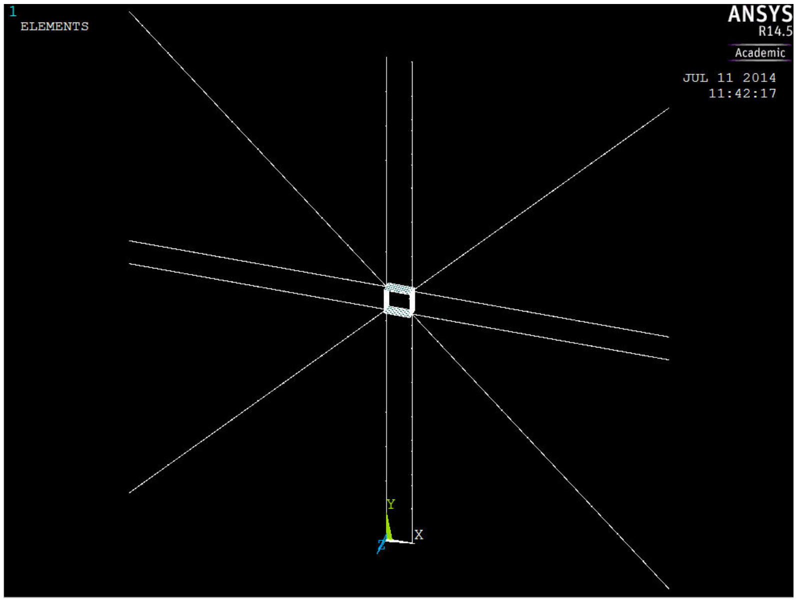


Figure 57. First Ansys model

The model uses shell elements to model the central dampener and pipe 288 element to model the cables. The pipe 288 elements are set to use a tension only setting, but actually model hollow cables.

If an out of plane force of 100 N is put on each keypoint in the central dampener (total 1200N), the web shows displacement in a transient analysis of 4 cm as shown in Figure 58.

Although this shows that the general principle works, the stresses in the cable cannot be found through limitations of the pipe 288 element.

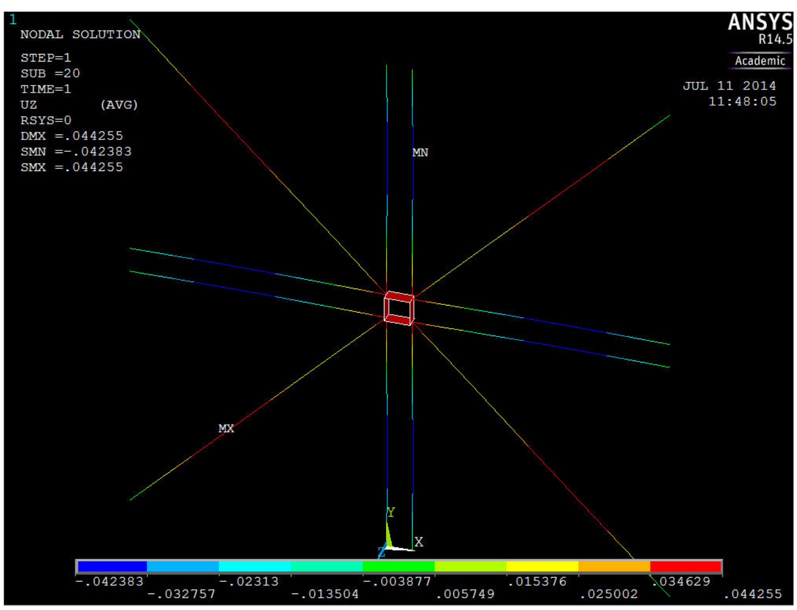


Figure 58. Displacement of the spider web as a result of applied out of plane loading

Second model

The second model, models one quarter of a circular radial only spider web with a stiff central dampener and uses symmetry to model the whole structure. The model is illustrated in Figure 59.

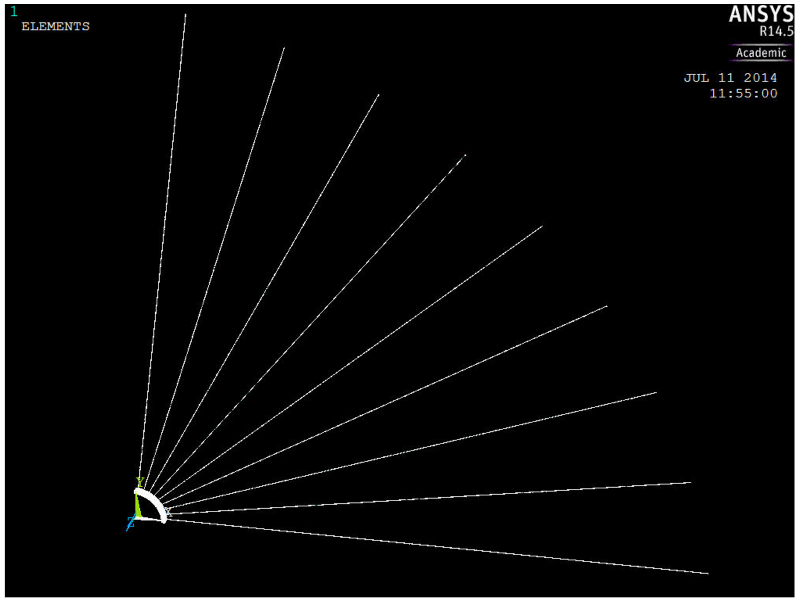


Figure 59. Second Ansys model

The model again uses shell element to model the damper and again pipe 288 elements to model the cables.

Applying an out of plane force on the nodes of 100 N on each node of the cable elements, giving a total pressure of 114 MPa on the surface results in the displacement pattern shown in Figure 60.

The total deformation of 1.54 m implies a significant energy absorption. Unfortunately the pipe 288 element does not allow for determination of the stresses.

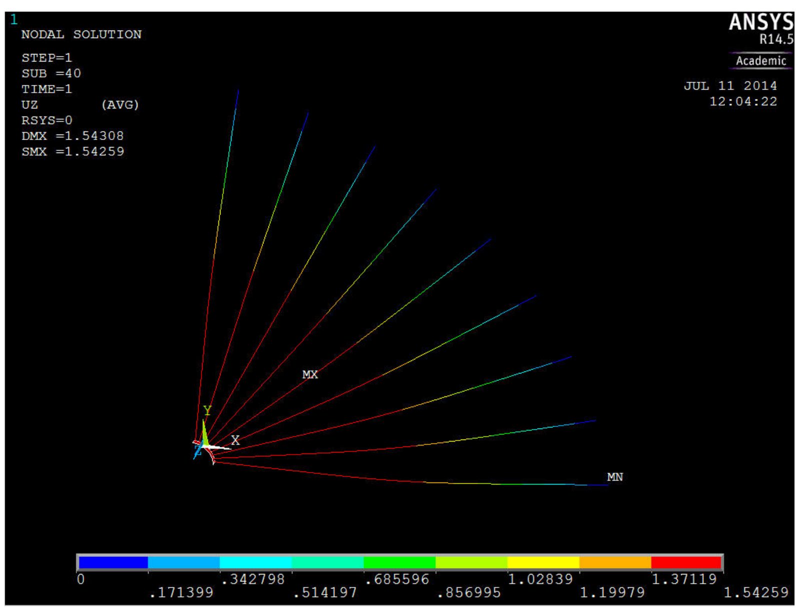


Figure 60. Displacement of second model as a result of evenly distributed force on the cables.

Third model

Although the model seems to work, the pipe 288 element which is a legacy element and not supported well in ANSYS 14.5 does not allow for the determination of stresses. A new model was made using beam elements to model the dampener as a steel doughnut and beam and link 180 elements set to model tension only elements. This is modern element advised by ANSYS inc. to model cables.

The model is shown in Figure 61.

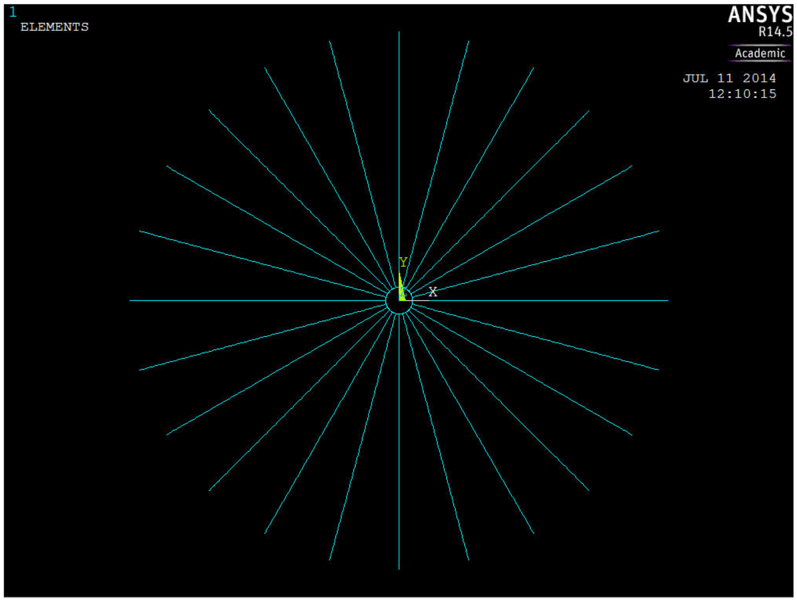


Figure 61. Third Ansys model, radial only web

Applying out of plane forces on the key points of the dampener results in Figure 62.

The problem with this model is that if forces are applied to the cables the model becomes unstable. It can thus not be used to model a realistic situation.

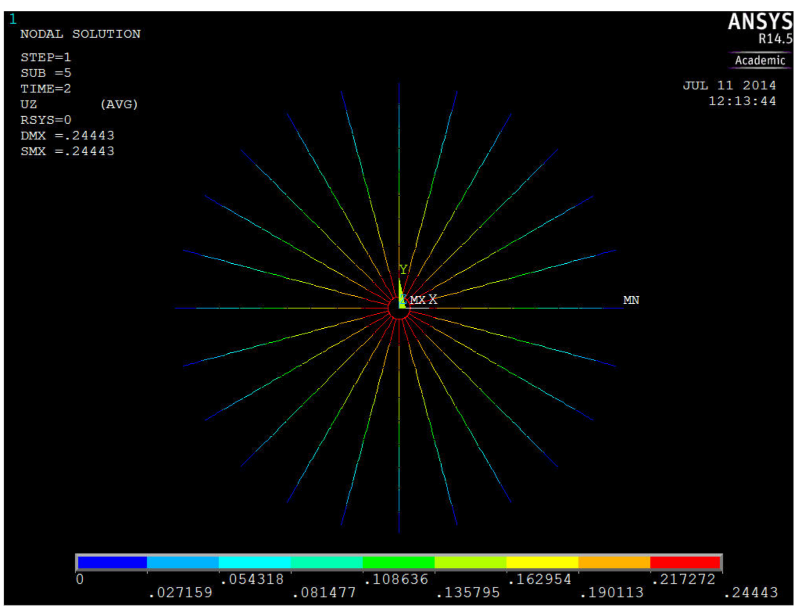


Figure 62. Out of plane displacement of model 3

Fourth model

Building on model 3 a real spider web was modelled. This is shown in Figure 63. This model was tested with very small out of plane forces applied to the key points of the dampener. The result is shown in Figure 64.

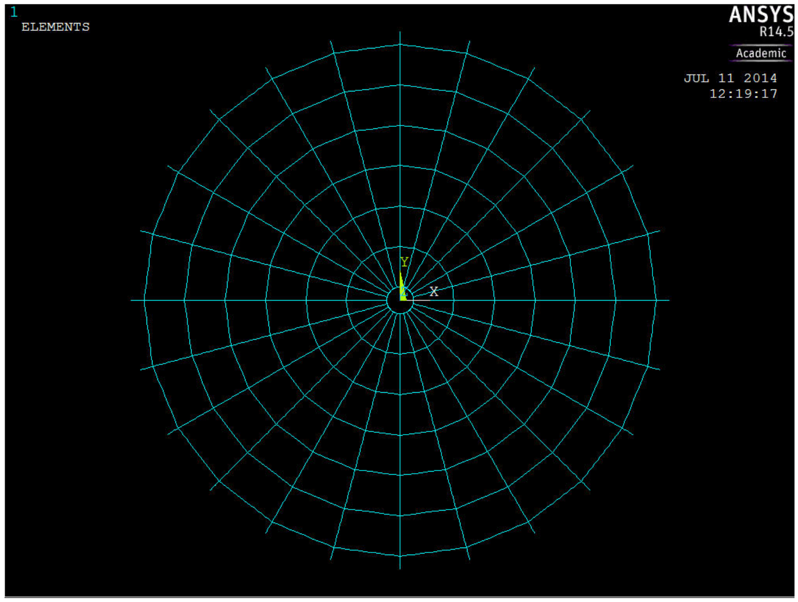


Figure 63. Fourth Ansys model, radial only web

If the forces are increased the model becomes unstable. If forces are applied directly to the cables the model also becomes unstable. This suggest that the lack of pre-stress causes large local deformations of the cables in this model which causes the calculation to fail at larger loads.

Although stresses can be calculated, the fact that no reasonable loads can be modelled does not allow checking of the stress state in the cable.

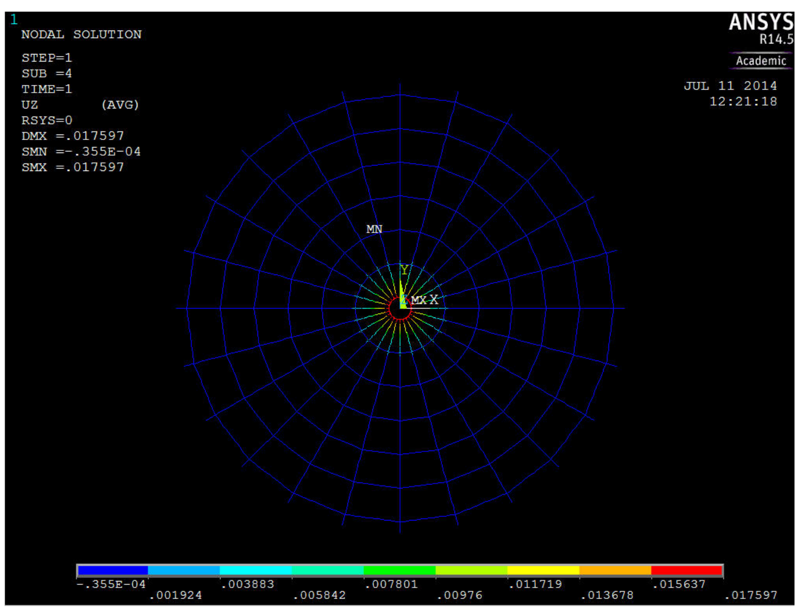


Figure 64. Results of fourth model

Discussion

Although modelling a spider web structure is possible using finite element modelling, the results are very dependent on the type of element used. With tension only link elements the calculation becomes unstable very quickly. With pipe elements the calculation can be made, but it is uncertain if the model is correct. A particular problem is introducing the pre-stress and the dampener system into the model. The cables need to be pre-stressed and dampened to realistically model the façade.

Pre-stressing is possible in ANSYS but there are no examples for web type structures, only for cables in concrete of complex vibrating rotors. The dampener can be modelled by changing the material model of outer section of the cable. However a better element type to model the cables needs to be found first. Without a better cable model, modelling the spring/dampener system is futile. Modelling the mass of the façade plates is easy and can be done by adding mass elements to the key points that are the basis for the lines in the web.

Conclusions

Modelling a spider web façade structure under blast loading should be possible in ANSYS. It however requires a tension only element to model the cables that can be pre-stressed. Alternatively the cables could be modelled as a series of hinged rigid elements. The question is however if this realistically models the structure, even though it avoids large local deformations of the cable due to locally applied loads.

If it is considered desirable to study this further it is suggested that a student uses the numerical modelling problem as the subject for his graduate thesis. The problem is too complex to do in a combined design/modelling project.

11. Structural principles

The design of this structure and its details are based on the biomimetic principles of a spider web. At a first place the natural aspects (material and typology aspects) of an orb were studied. This study answered the main questions of how and why the web works in this way. Chapter 1 contains all the details regarding these answers. After the understanding of the natural behaviour of the web, we put our emphasis to rationalize these features simplifying the geometry and preparing the base of the design with the development of initial drafts. At the last stage, an effort was made to translate the initial ideas into a real design, focused on the geometry of the Markthal envelope.

11.1. Structural scheme

The system consists of two parts, the primary and the secondary structure. The primary structure is consisted of a central damper connected to four stiff cables and the secondary structure of the radii and the spirals. The figures on the next page depict the build-up of the structural system.

Damper

Trying to mimic the main feature of the spider web , dissipation of energy, a central damper was introduced as the core of this design.

According to the assumption that the explosion is happening in a long distance of the facade, when blast wave invests the facade the pressure could be assumed uniformly distributed on the facade area. As a consequence of this assumption, the most adverse loading case appears in the centre of the facade and therefore this should be the position of the damper.

Cables

Given the size of the central damper it is obvious that a rigid structure is required to transfer the load of the damper to the massive concrete frame. A cable net structure is developed consisting of four rigid cables. Given the restricted time for this thesis, the details of this structure were left for future investigation and development. However, the design of this structure was inspired by the Rocker Façade Support System as used in Poly Corporation headquarters in Beijing.

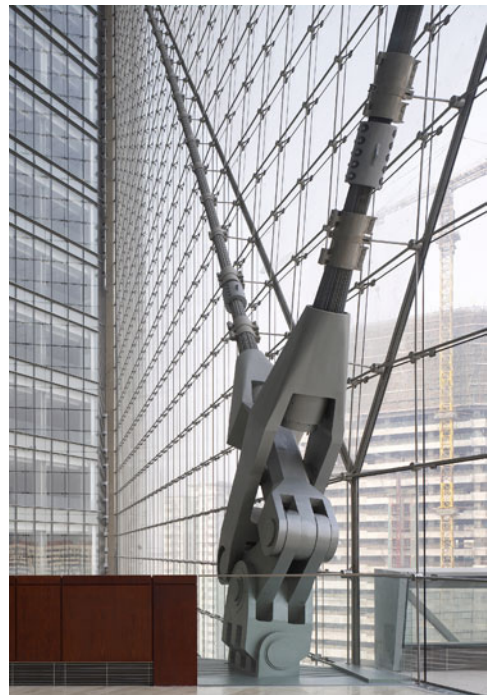


Figure 65. Rocker Façade Support System, Poly Corporation headquarters (Beijing)

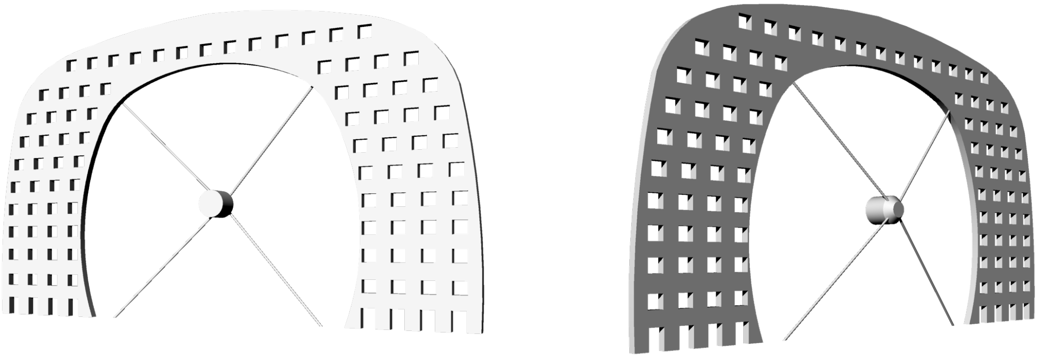
Radii

The radii were designed as steel cables (diameter Φ=36mm) connected to the central ring of the damper. The one end is pre-stressed and connected to the massive concrete wall with a spring systems (see detailing) and the other end is simple connected to the central ring.

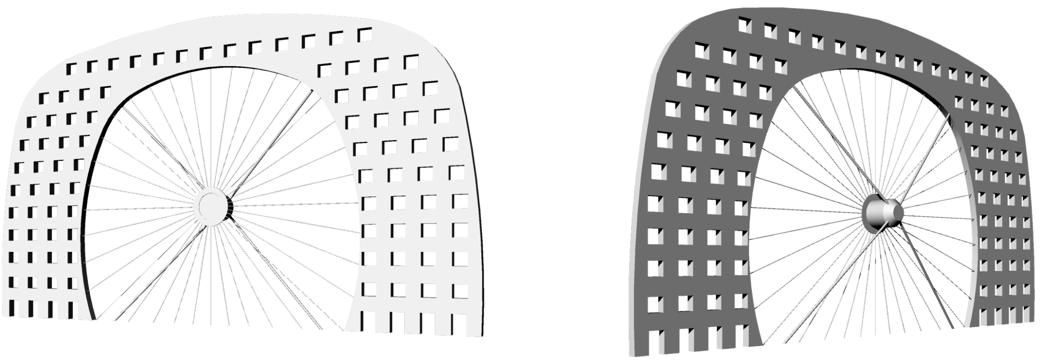
Spirals

The spirals are considerably thinner steel cables with diameter Φ=10mm connected with the radii.

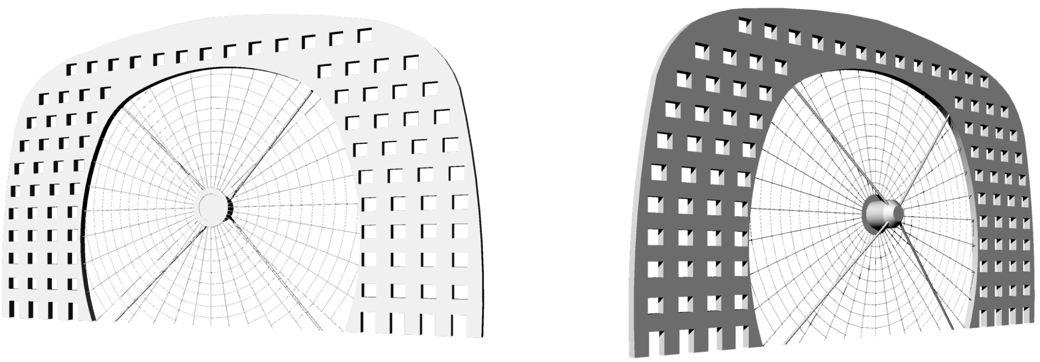
The number of the radii and spirals, as well as their cross sections, is the result of the consideration of realistic glass dimensions (see detailing).



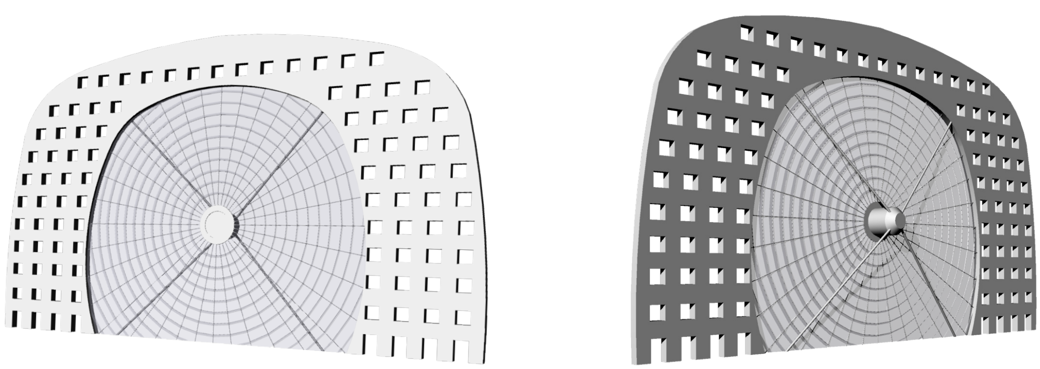
Primary structure: damper and cables



Secondary structure: radii cables



Secondary structure: spiral cables



Cladding: glass panes

11.2. Load path

The main design principle of this system was the ability to absorb higher amounts of energy. Designing a system like that, the maximum tensile stresses in glass panes can be reduced since the air blast pressure acting on the façade will not completely transform into elastic energy. In this way glass breakage could be preventing or in case glass pane break then the velocity of glass splinters that detach from the inter layer is significantly reduced and the consequences or hazards are lower.

Moreover, this type of system could allow unrestrained deflections and warping of the glass panel avoiding rigid restraint and consequently preventing the glass from high stresses at the points of supports.

Figure 66 and Figure 67 present the Load path mechanism that shows how that the system can withstand the blast loading transferring it to the concrete load bearing wall and finally to the foundation.

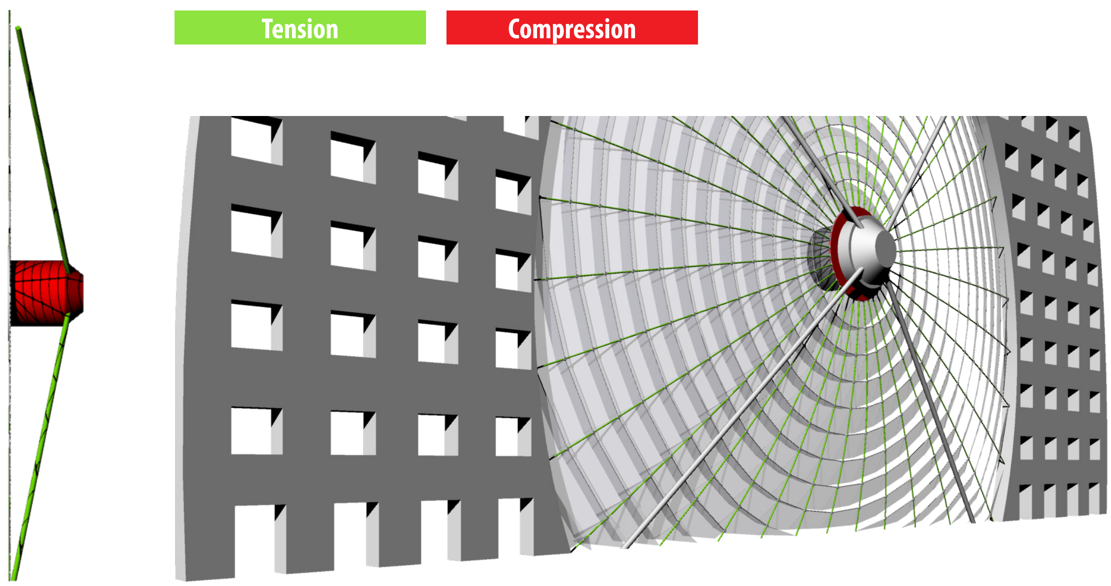


Figure 66. When the blast load invests the facade the load is transferred to the radii and the ring

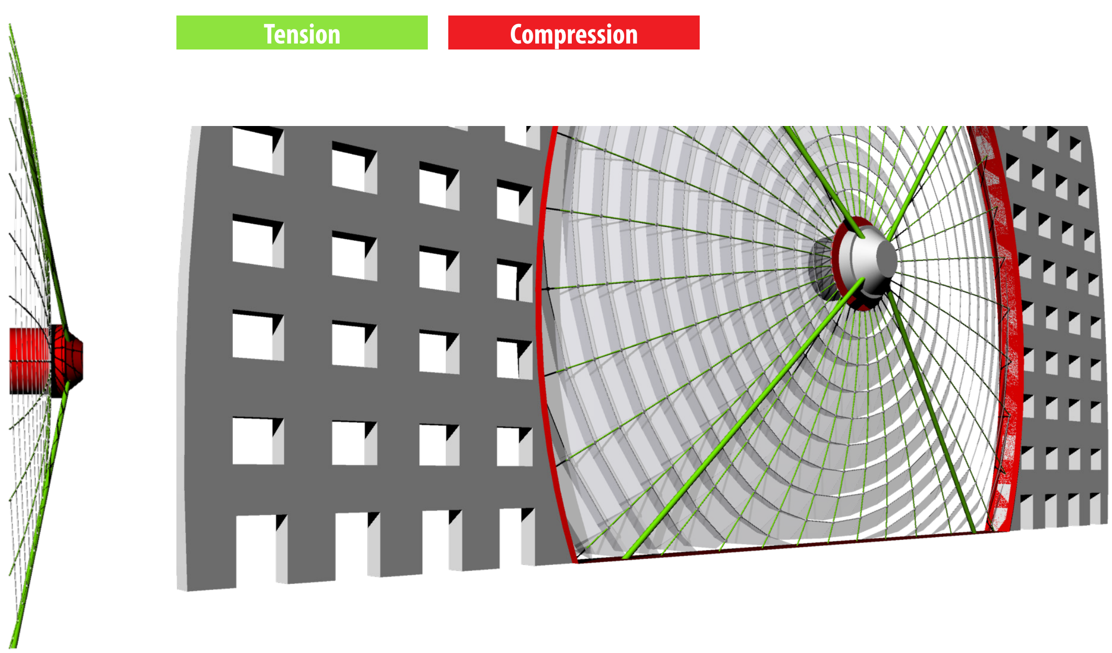


Figure 67. In the second phase the main cables transfer the load to the concrete load bearing wall

Mass damper

The idea of a mass damper is not new, however mass dampers are mostly used in automobile industry. In the building industry dampers are mostly massive concrete blocks or steel bodies mounted in skyscrapers or other structures and moved in opposition to the resonance frequency oscillations of the structure by means of springs, fluid or pendulums. Dampers in the building industry are limited to deal with unwanted vibration may be caused by environmental forces acting on a structure, such as wind or earthquake. The largest mass tunned damper is located in the centre of the skyscraper of Taipei's World Financial Center.

Figure 68. Tuned mass damper in the top of Tapei's World financial Center tower.

However no use of dampers against blast loading on a cable net facade has been made so far. The design and function of the damper are shown in Figure 69.

Definition: tuned mass damper or harmonic absorber, is a device mounted in structures to reduce the amplitude of mechanical vibrations. Their application can prevent discomfort, damage, or outright structural failure.

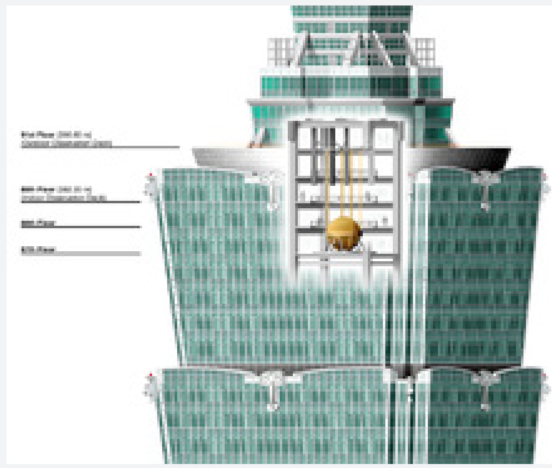


Figure 69. Location of the tuned mass damper in Tapei World financial Center tower

12. Detailing

The initiative for start designing this structure was the mimicking of the main aspects of the spider webs. From the very beginning the efforts were concentrated on the 3 types of connection of the system, as they appear in Figure 70.

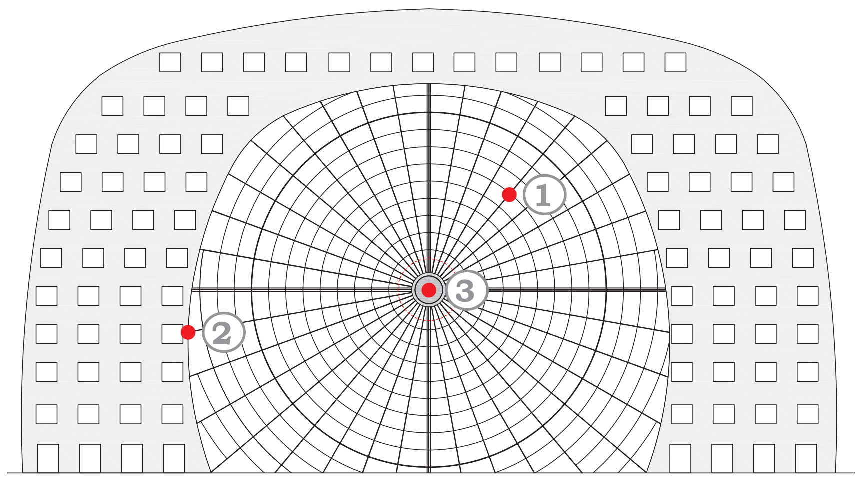


Figure 70. Overview of interesting detail points

Glass- Radii connection (1)

From the background research was established that the problematic behaviour of the existing cable net façades focuses mostly on the glass breakage and consequently at its connection with the cables. In order to give a design solution the following steps were followed:

i) Selection of the appropriate glass type and interlayer as described above.

Concerning the cladding material of the facade, glass was a restriction from the existing design. The design of the glass connection was made with the assumption that glass will survive the explosion. The selection of the glass type as heat strengthened and of the SGP interlayer was made based on the background research regarding the Types of glazing and behaviour under blast loading. More information are offered at the grey pages.

ii) Design of a connection mechanism inspired by biomimetics.

This mechanism allows a) the fully unrestrained movement of the one side of the glass pane while b) the other side is connected on the radial with two "ball" hinged connections.

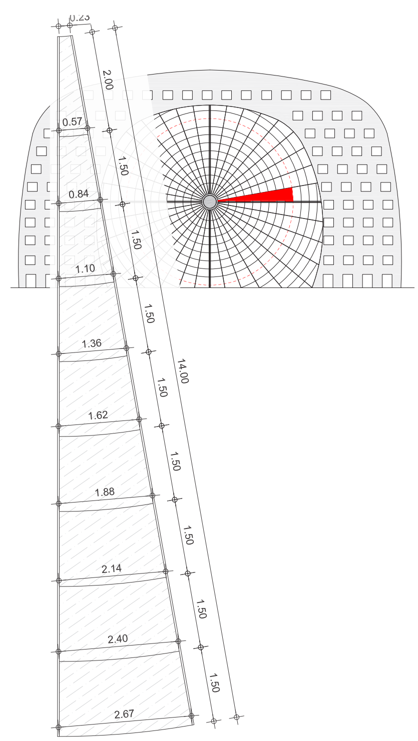


Figure 71. Dimensioning of glass panes in single strip

Selected glass type

(based on Oikonomopoulou 2012)

Glass is divided into three main categories regarding its strength: (a) annealed (b) heat-strengthened and (c) fully-tempered glass.

Annealed glass is the raw glass that comes through the processing. It has low residual stresses that allow for cutting, drilling or grinding.

The strength of annealed glass can be enhanced through a heat treatment process, resulting to the other two types of glass: heat-strengthened and fully tempered. In this process the glass is heated to approximately 620-675°C and subsequently rapidly cooled by air jets. As the outside surface cools and solidifies more rapidly than the inner core of the glass, a surface compressive residual stress and an interior tensile residual stress results in the glass. This compressive residual pre-stress at the glass surface effectively enhances the tensile resistance of the glass [Louter, 2011]. Any drilling, cutting and grinding of these two types of glass should be done before the tempering process.

Fully-tempered glass has the highest level of residual stress and therefore the highest (tensile) strength. However it was considered inappropriate for the load-bearing components, because of its breaking pattern: due to its high pre-stress level, it shatters into very small fragments that do not allow for any integrity after breakage.

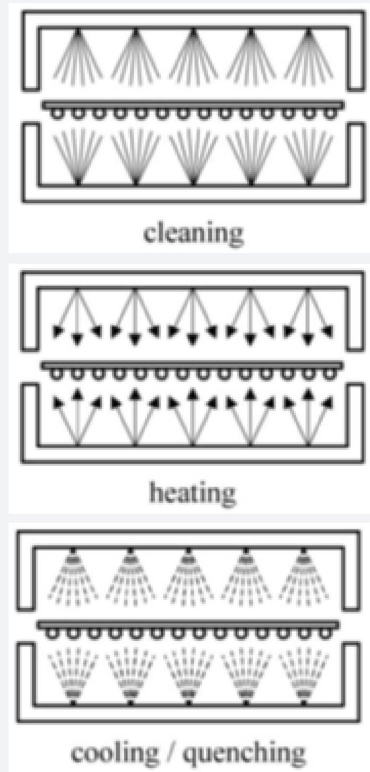


Figure 78. Schematic representation of the tempering process (Worner et al. 2001)

Heat-strengthened glass has a lower level of residual stresses compared to fully-tempered, due to a lower cooling rate during the tempering process. Regarding damage sensitivity, it performs similarly to annealed glass with an also similar cracking pattern (see figure 4.7): it breaks into large fragments which allow the transfer of (compressive) forces, especially through overlapping sheets [Bos, 2009].

Therefore, heat-strengthened glass was opted for the load-bearing structure as the most appropriate material, since it breaks in big segments that are able to still carry load and has a much higher (tensile) strength than annealed glass.

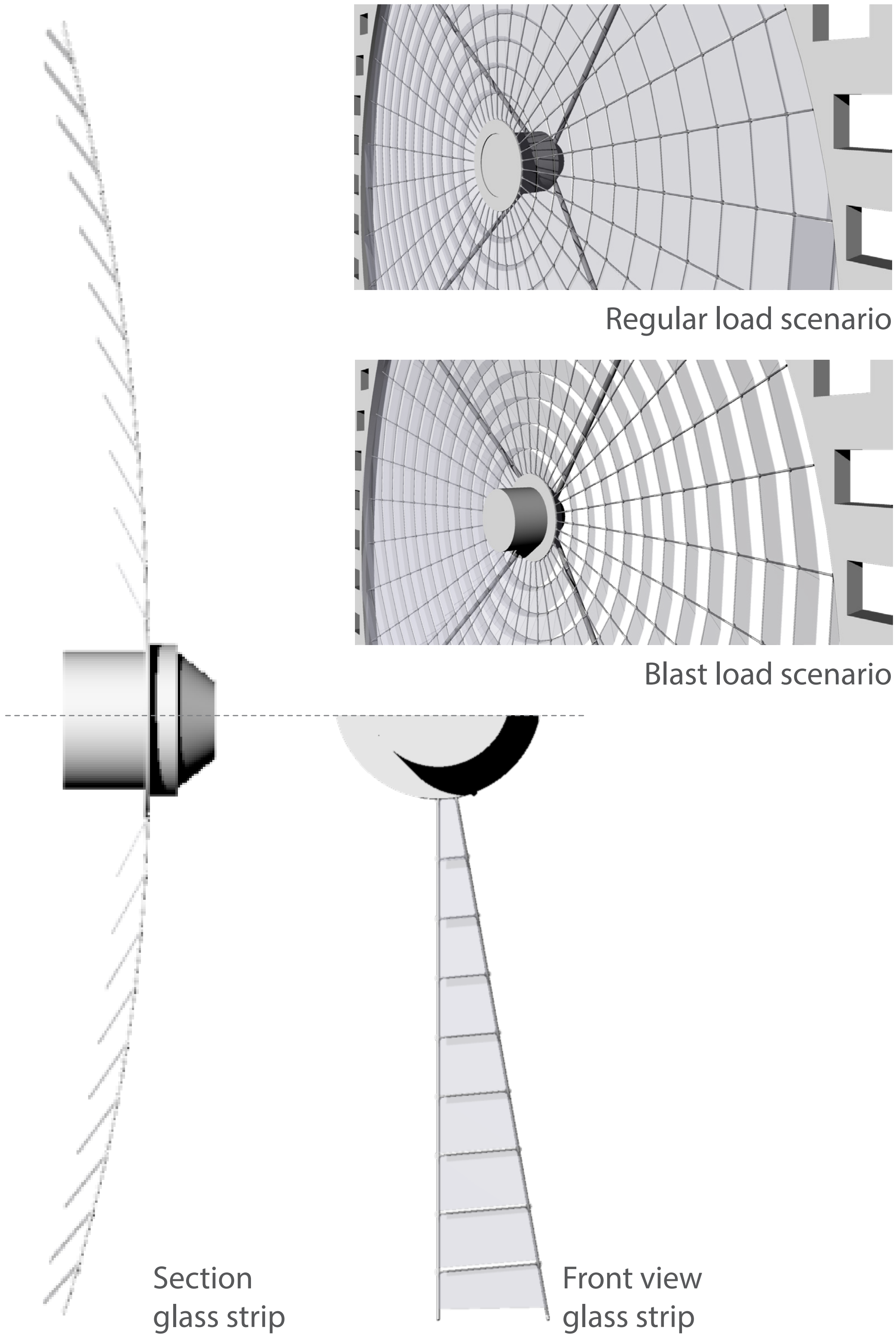


Figure 72. Glass layout and rotation mechanism

Selected Interlayer for lamination

(based on Oikonomopoulou 2012)

Laminated glass consists of two or more glass panes that are bonded together by means of an adhesive interlayer, either foil or resin. Foil interlayers are the most commonly applied for laminated glass. The foil is bonded to the glass sheets in autoclaves, under elevated temperature and pressure. The main purpose of the (foil) interlayer is to keep the glass fragments together (see figures 4.10-4.11) in case of glass fracture to prevent human injury. But equally importantly, foil laminated glass allows for an enhanced post-breakage behavior: As the glass fragments stick to the foil, a residual structural capacity is obtained through an arching or interlocking effect of the glass fragments [Louter, 2011]. The extent of this post-breakage capacity depends strongly on the applied glass type (annealed, heat-strengthened or fully tempered) and the applied interlayer type.

The most common foil interlayer is PVB (polyvinyl butyral foil). Under elevated temperature and pressure, this foil is bonded to glass sheets in autoclaves. This material has little strength and stiffness of its own and is mainly used to prevent glass shards from coming off. It usually relies on the load carrying capacity of some unbroken glass sheets for residual strength [Bos, 2009]. Other examples of foil interlayers are EVA (Ethylene Vinyl Acetate), which is commonly used in solar applications and SGP (DuPoint's SentryGlas®). This interlayer has been developed for hurricane, vandalism and burglary resistant glazing. SGP has already been applied in the glass structure of the Apple Stores in New York and Boston, laminating components up to 15 meters long.

Compared to common PVB, SGP has 5 times higher tear strength and makes the laminated component 100 times more rigid [O' Callaghan, 2009]. In addition, due to its relatively large thickness and its low viscosity [32] when heated during the lamination process, the SG interlayer easily conforms to dimensional inaccuracies on the glass and easily flows around reinforcement sections embedded in the interlayer [Louter, 2011]. For all these reasons SGP was considered the most appropriate choice for the load-bearing structure of the shelter.

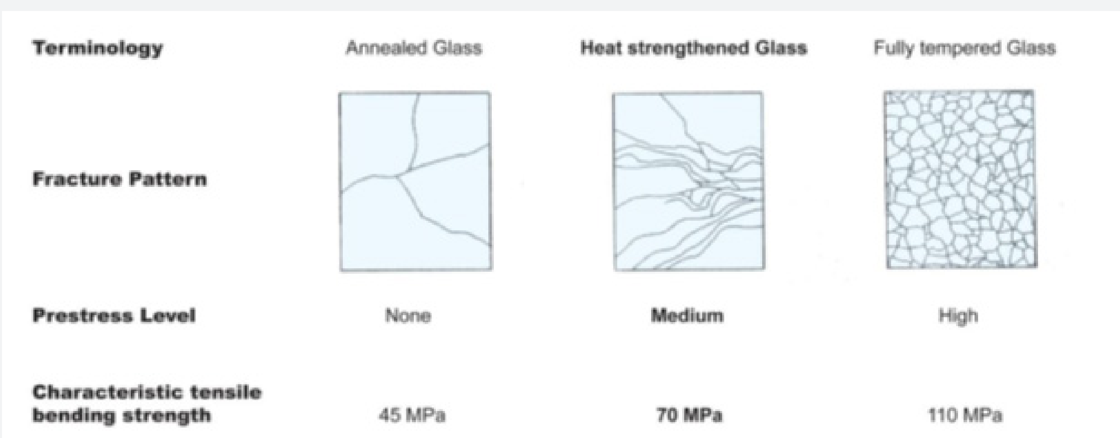


Figure 79. Types of glass and breaking patters [Belis, 2012] and characteristic tensile bending strength of the different types of glass according to EN 572-1:2004; prEN 13474-1, 1999

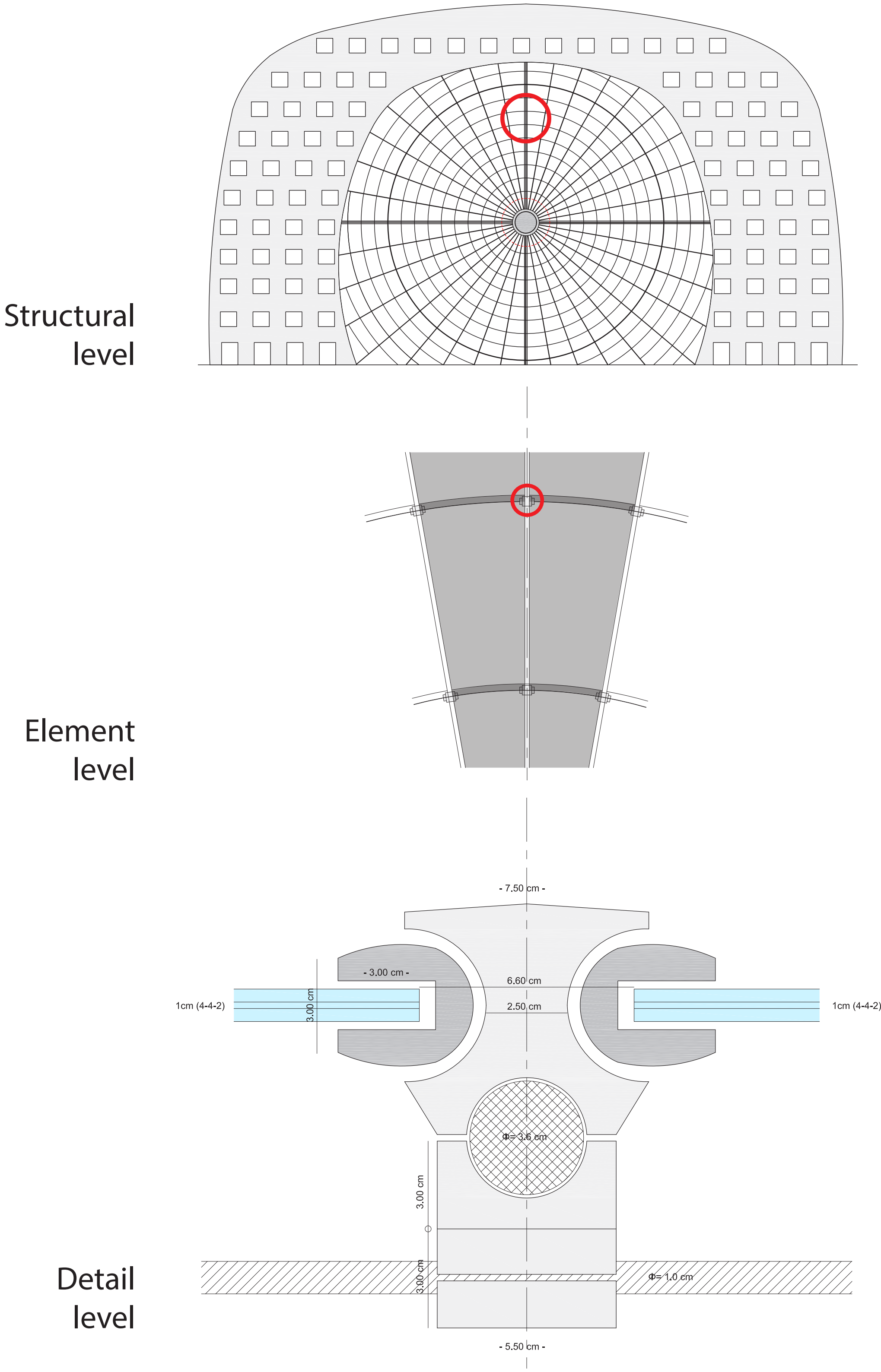


Figure 73. Principle detail of glass connection

Mimicking feature: Best balance of strength and toughness (2)

The idea was the use of spring systems as end cable connectors. Studies have proved the effectiveness of such mechanisms.Several types of elastoplastic connectors for building cables has been already produced.

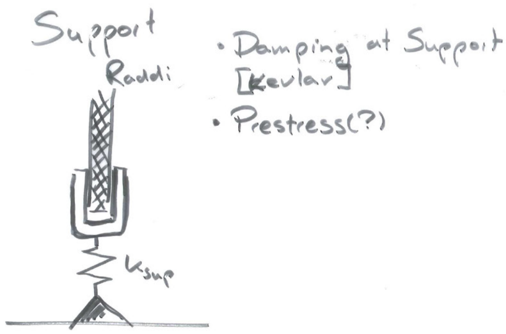


Figure 74. Sketch of initial support structural concept of connection 2

Therefore, the detailed development of such a mechanism was out of the scope of this research.

Figure 75. Patented cable-end-connector/ before and after fuse breakage in phase 2 (Gartner)

Mimicking feature: Hub (3)

Since the hub was a central characteristic of the spider web, its imitation was a primary consideration.

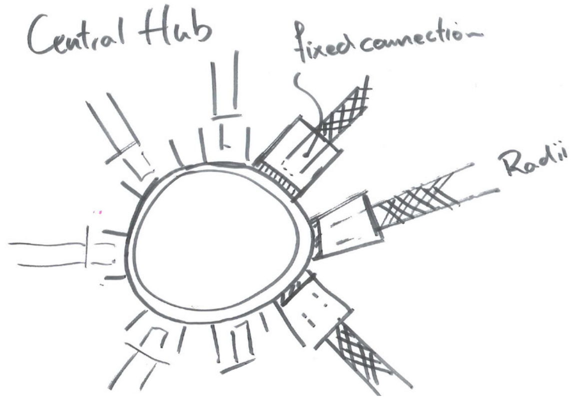


Figure 76. Principle sketch detail of the hub concept connection 3

The radii are rigidly connected to a central steel ring attached to the damper.

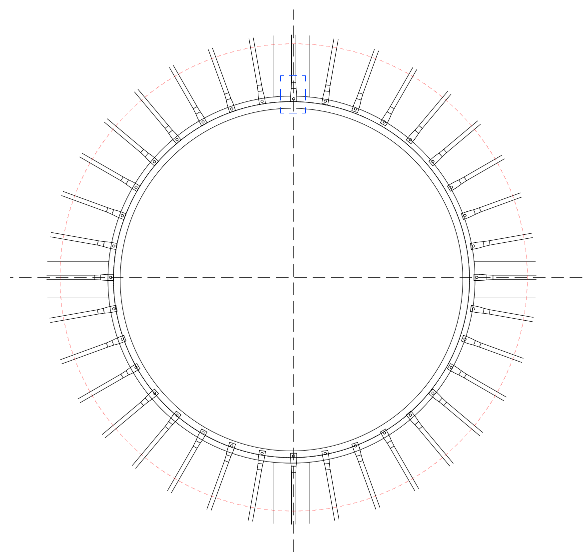
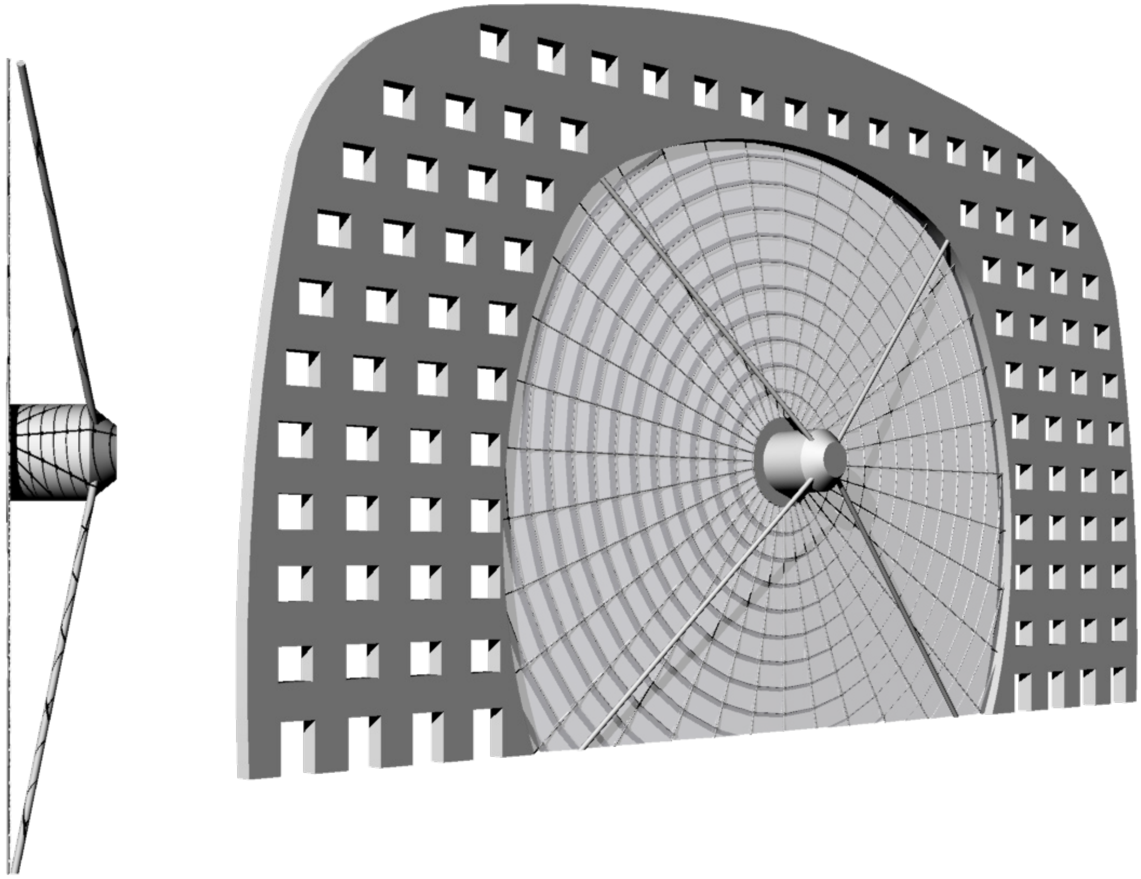
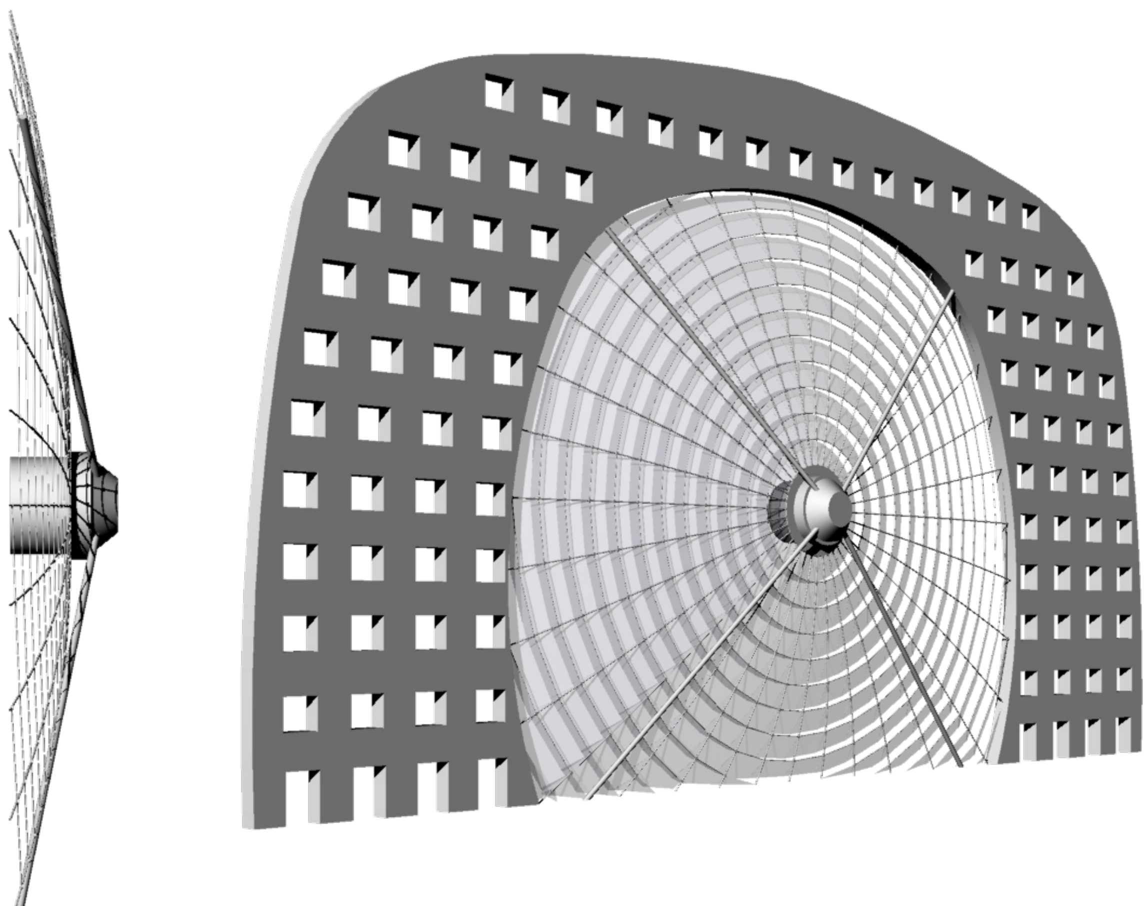
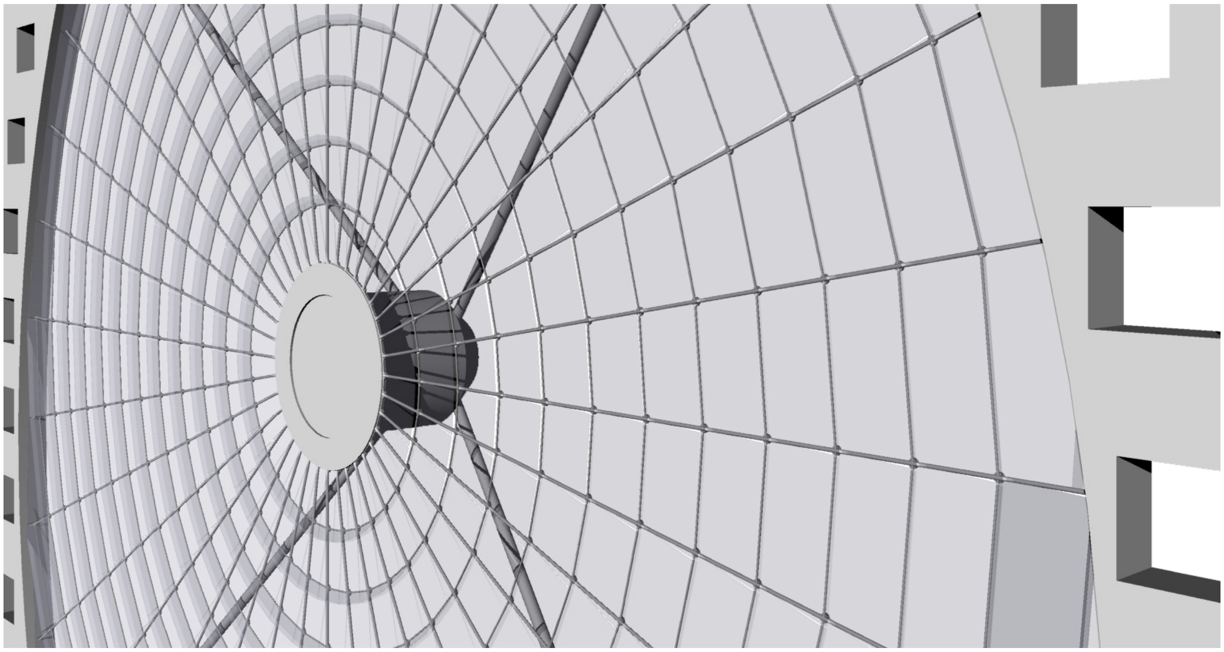
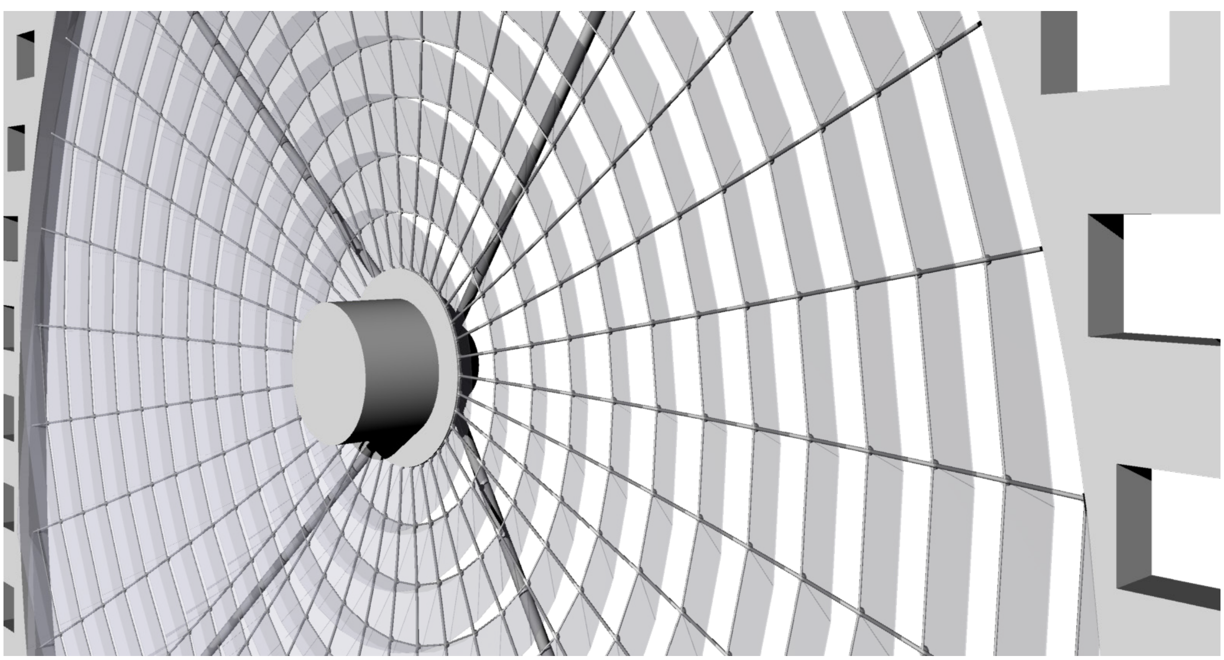


Figure 77. Front view of the final layout of the central hub ring with 36 radii connectors









IV. Conclusions

Discussion on the research objectives, conclusions limitations and recommendations for further research

13. Discussion and Conclusions

This thesis research demonstrates that it is possible to envision existing cable net facades as structures able to withstand blast loading, using a biomimetic approach.

13.1. Reflection on research objectives

In chapter 1 the main aspects of biomimetics are presented. Through a quick study regarding natural compliant structures, it became apparent that a spider web is a proper case of a lightweight structure that can withstand impact loads disproportional to the dimensions of the web.

In respect to the research of the structural behavior of the natural spider web, we concluded that its main aspects cannot be simply scaled up to conventional building dimensions. The reason for that is twofold:

Firstly, the existing studies highlight the importance of the material in the structural performance of a spider web and they all agree that the silk's way of stretching and the discreteness of the web enhance its resistance against damage. Currently, spider silk is not commercially available and therefore it cannot be considered as a building material.

Secondly, perhaps the most interesting feature of the spider web mechanism to resist damage when subjected to impact loading – the "sliding connections" of spirals and radii (paragraph) – is not scalable, due to the difference in the nature of the loading. Specifically, the discussed "sliding" mechanism works for targeted (local) loading on the structure, while the examined loading (for the purpose of this thesis) is restricted to blast (uniform) loading on the structure.

In respect to the form of the spider web the research established that its increased damage tolerance is an attribute of the discreteness and the hierarchical design of the web. This characteristic was partly mimicked while the simplified web shape was successfully imitated in the macro scale of the building façade.

The research of the existing cable net facades in combination with the nature of blast loading established the reasons of causing poor performance against blast loading. It was recognized that the basic problem was focused on the glass panes as they represent the primary source of damage in glazing curtain walls subjected to air blast, since they mainly absorb the incoming energy due to the explosive blast wave. Therefore, it is of highly importance high deformations to be permitted in all connections. This finding was critical on the design of the end cable spring systems as well as on the design of the connection system. However, reviewing the blast loading aspects, for higher blast load assumptions additional mechanisms are required that reduce stresses and forces absorbing higher amounts of energy and reduce the load acting on the glass panes.

13.2. Reflection on design objectives

Based on the initial conclusion, it was clear that trying to imitate fully the main spider web characteristics was not a reasonable strategy and therefore alternative approach should be followed. A simple analogy between an individual spider silk thread and a construction cable made of spider silk would be a crassly assumption, risking the validity of the calculations. Therefore, we focused on mimicking the nonlinear stiffening behavior of a spider web and the discreteness of its typology using conventional building material elements such as steel cables and spring systems.

Although modelling a spider web structure is possible using finite element modelling, the results are very dependent on the type of element used.

Regarding the form of the web, in Chapter 1, we discussed briefly the structural efficiency of this typology and the advantages over an orthogonal cable net. Moving one step forward, with the use of the ANSYS model, we investigated the possibility of using this theory in order to redesign the conventional cable net glass façade, in respect to their problematic performance against special loading.

In order to answer if this system could also be able to withstand blast loads we followed two different methods; hand calculations and computational calculations. Although the results of the hand calculations suggested the need of a more detailed calculation approach, they confirmed the feasibility of the concept. Given the complexity and the nature of the loading and the extensive dimensions of the examined façade, it became apparent from the computational calculations that a supportive mechanism was necessary for enhancing the blast response of the structure.

Reviewing the basic aspects of blast loading as well as the whole building response to blast damage Chapter 1, it was evident that the most effective way to improve the blast response of a structure is to dissipate a considerable part of the blast wave. The research about energy absorption mechanisms suggested the use of a core damper centrally and spring systems as end cable connectors.

A particular problem was to introduce the prestress and the dampener system into the model. The cables need to be pre-stressed and dampened to realistically model the façade.

Moreover, evaluating the overal design strategy we drew the conclusion that the different aprroaches were equally important. The hand calculations can save valuable time of computing complex models in case that the concept is not realistic, while finite element model is essential for the understanding of the complexity of the problem.

Modelling a spider web façade structure under blast loading should be possible in ANSYS. It however requires a tension only element to model the cables that can be pre-stressed. Alternatively the cables could be modelled as a series of hinged rigid elements. The question is however if this realistically models the structure, even though it avoids large local deformations of the cable due to locally applied loads.

The design strategy gave us the confidence that theoretically this structure can withstand the specific blast loading and consequently the motivation to investigate design possibilities of the structure. The outcome of this investigation is visualized by drawings included in the Design part, offering the optimism that the realization of the design concept is possible.

To recapitulate, the main conclusion can be stated as "Although several aspects need more detailed evaluation, as the analysis and the concept design suggests, the proposed blast enhanced spider web facade can be realized, following blast design and biomimetic principles"

The secondary conclusions drawn from this research can epigrammatically presented as follows:

- Although modelling a spider web structure is possible using finite element modelling, the results are very dependent on the type of element used.
- Modelling a spider web façade structure under blast loading in ANSYS should be possible but it is questionable the realistic modelling of the structure.
- The main aspects of spider webs cannot be simply scaled up to conventional building dimensions but some of them can be mimicked with the use of conventional building components.

14. Limitations & recommendations

Spider silk not commercially available

As it is obvious of the aforementioned the biggest limitation of this thesis was the fact that the spider silk is not yet commercially available. However, as we have discussed in Paragraph artificially manufactured spider silk is a reality and therefore it is matter of time to be commercially available. When this happens, this research can be used as base for the design of a cable net façade made of actual spider silk material.

Restriction of the case study

An also important limitation was the chosen case study, since it consists Europe's largest cable net façade and both the extensive dimension and the existing design (with glass as cladding material) were limited factors regarding the blast design. It is apparent that, in order a facade to be entirely blast proof extreme measures need to be taken, that change drastically the appearance of the façade. Therefore, for the purpose of this thesis, the concept design responds only to the chosen blast scenario.

Investigation of the "hub" position

The initial parametric model was set up in a way that coordinates of the "hub" were variables as well. Fig. The intention was to investigate the optimal position of the hub regarding the blast loading. In the limited course of this thesis the investigation of the basic principles was a priority over the optimization of the hub position. Nevertheless, it is recommended for future investigation since it consists an very important parameter for the success of the whole system against blast loading.

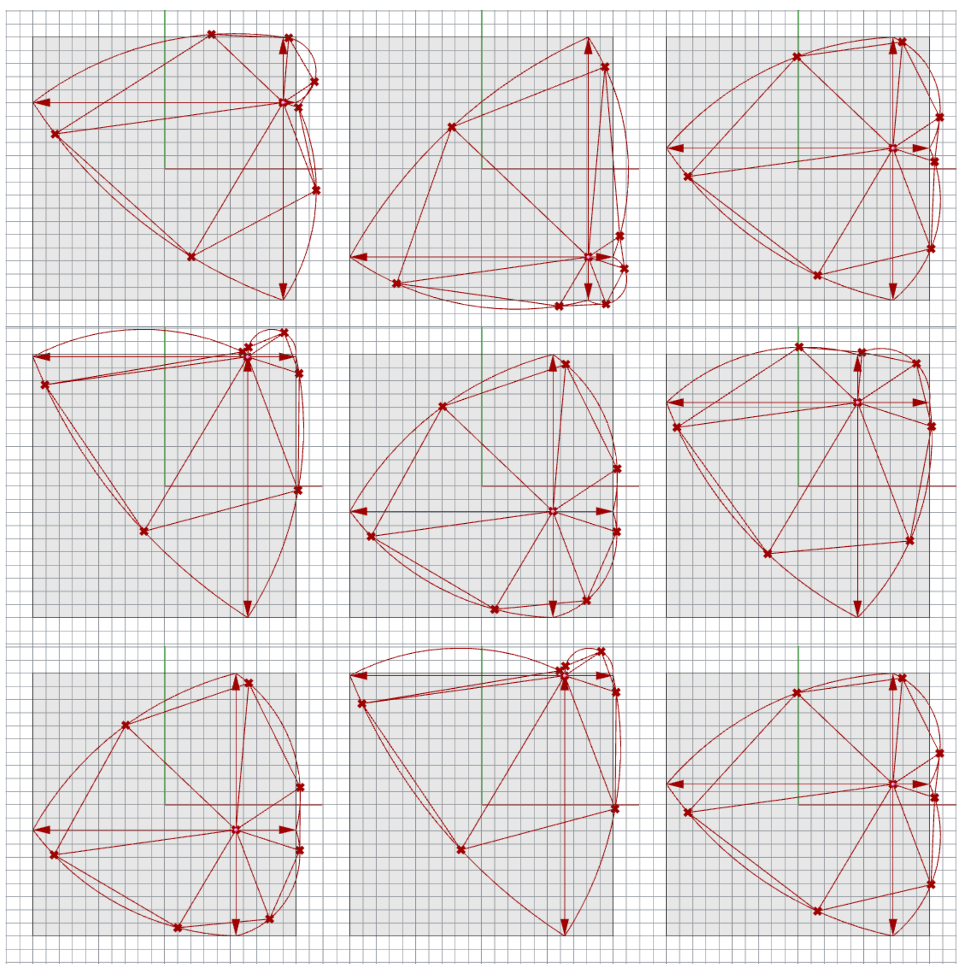


Figure 80. Preliminary investigation of the hub position for different web topologies

Construction of a scaled model

Finally, the most important recommendation for future research on the topic is the construction of a Mock-up from the very beginning. The complexity of the geometry, especially in the deformed state, made very difficult the understanding of the overall behavior but also the design of the detailing. Moreover, the validation of the design would be easier, testing the mock-up under physical impact loading. Valuable time would be gained avoiding using complicated modeling techniques and the whole design procedure and also the result would be unquestionable more motivating.
It should also be mentioned that the restricted period of time for this thesis didn't allow further investigation of the connection details closer to the compression frame of the concrete load bearing wall of Markthall.

Design of the façade damper

The extensive design of a damper was out of the scope of this thesis, since is more a work of mechanical engineer, and only the basic idea was introduced in the conceptual design of the system. Nonetheless, the development and further investigation of this idea might be valuable for the construction of blast proof lightweight systems.

Investigation of building physics

The glass system mechanism was developed specifically to secure that glass panes will survive in case of an explosion and stay in place till the vanishing of the blast phenomenon. However, further development and investigation would be interesting concerning the thermal gains and ventilation of the building.

Numerical modelling problem as a main subject for graduate thesis.

If it is considered desirable to study the structural behaviour of this system further it is suggested that a student uses the numerical modelling problem as the subject for his graduate thesis. The problem is too complex in a combined design/modelling project.

Inspiration for the glass- connection mechanism

1.Mimicking feature: sliding connections

In order to mimic this feature the idea was to produce a cable with a variable cross section in combination with a connection that could work as a stopping mechanism. Fig. 2 presents the brainstorming that led us to this solution and Figures illustrate the detailing of the conceptual connection.

Moreover, to the question how to mimic the progressive collapse mechanism (as explained in Paragraph 7.4 , Conncetions), connecting the spirals in the middle could be an answer. This type of connection could be feasible, since the concept is already patent (as Figure 84 presents)

In a situation under regular loading the connection would be stiff enough and the cable would work as one uniform cable. In a situation under blast loading the connection would rupture, releasing the cables to move freely. The gain would be the energy dissipation/ transformation by the controlled collapsing of the spirals, in order to protect the main loadbearing system (radii).

Both of these ideas finally abandoned because of the complexity of the problem, as well as the different nature of loading as explained detailed in the conclusions (Chapter 8).

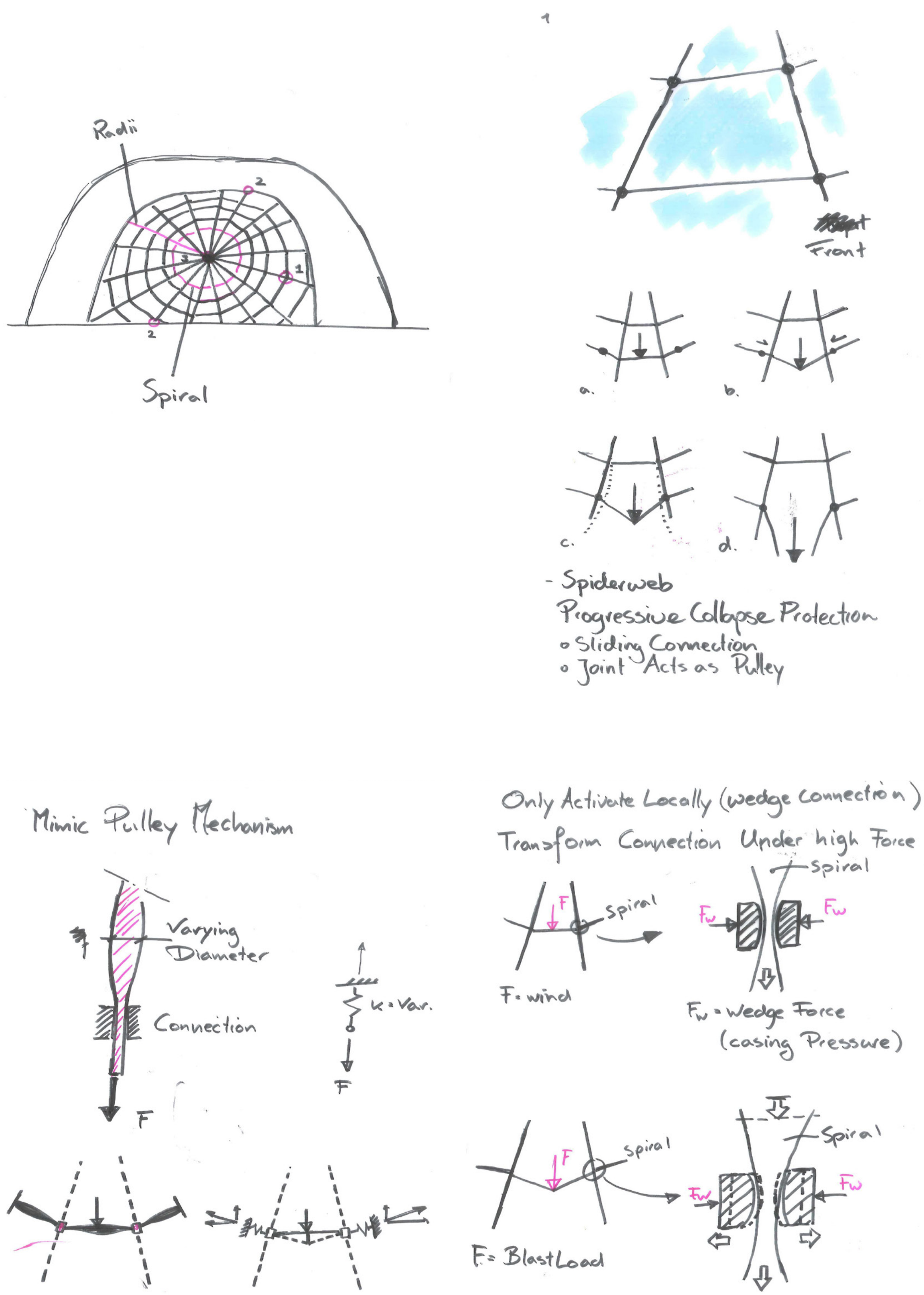


Figure 81. Brainstorm sketches for investigating spider web sliding connection mechanism

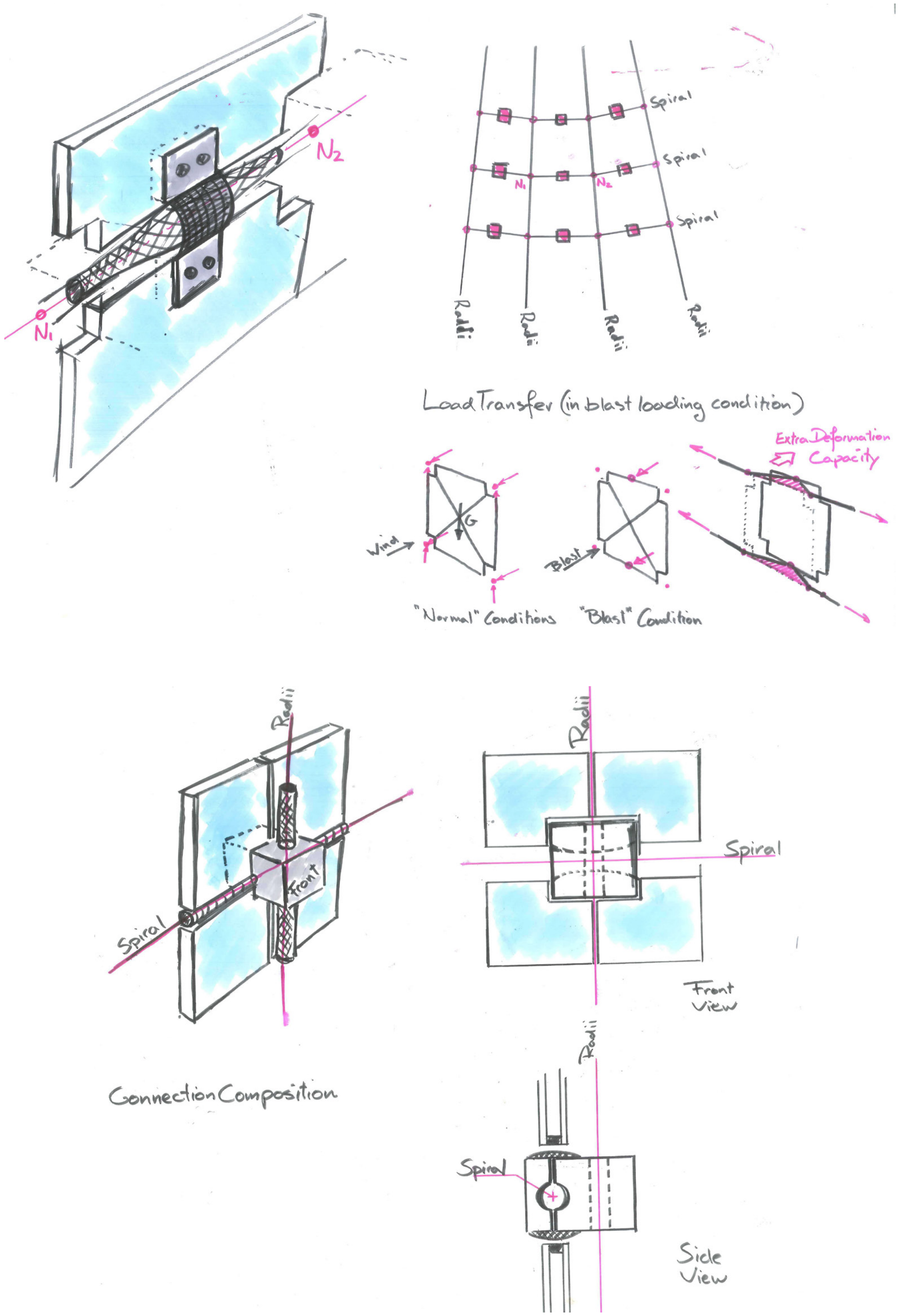


Figure 82. Sketch design of connectors between (top) the glazing and spirals and (bottom) glazing, radii and spiral elements

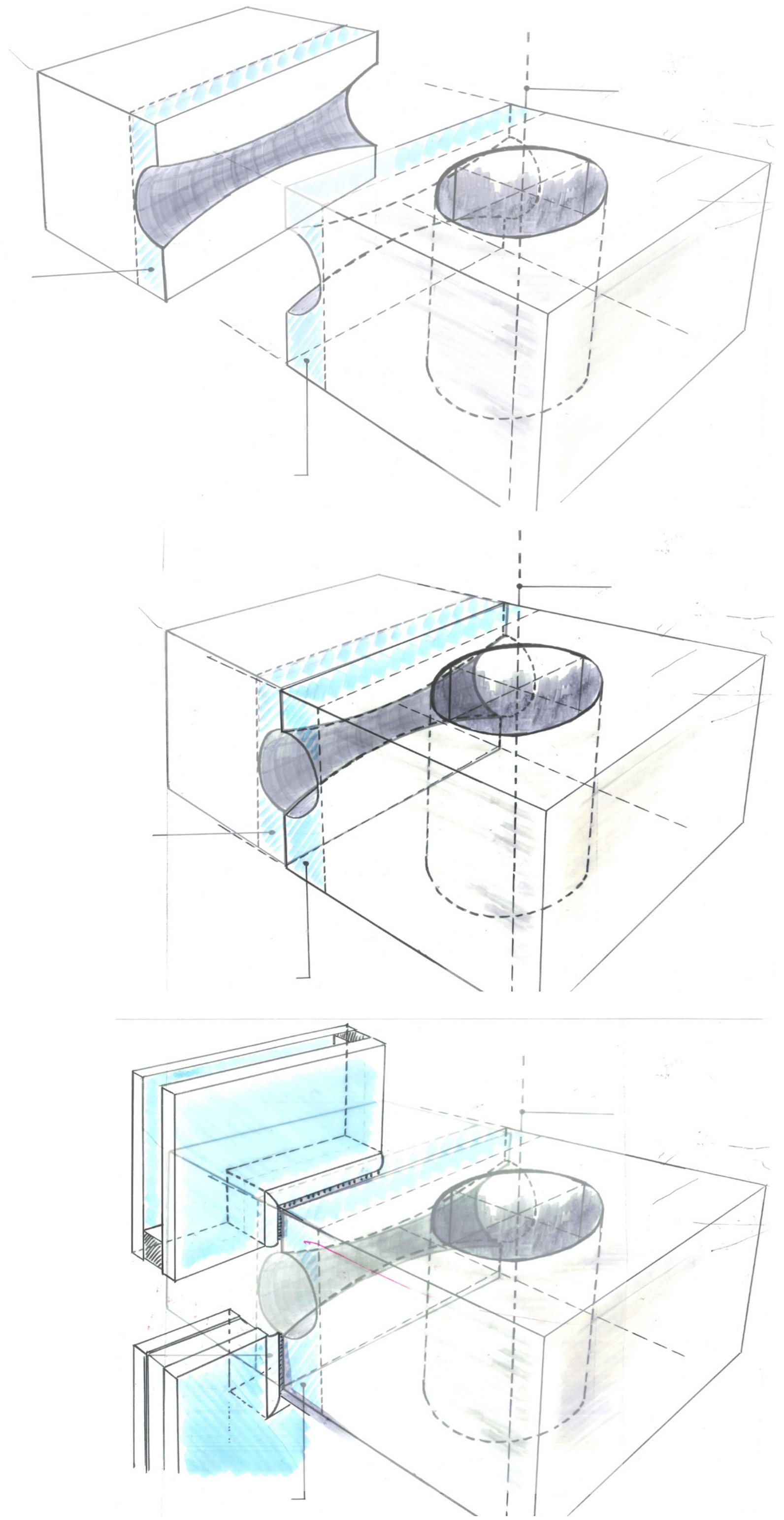


Figure 83. Concept detail of sliding connection to mimic the spider connection behaviour

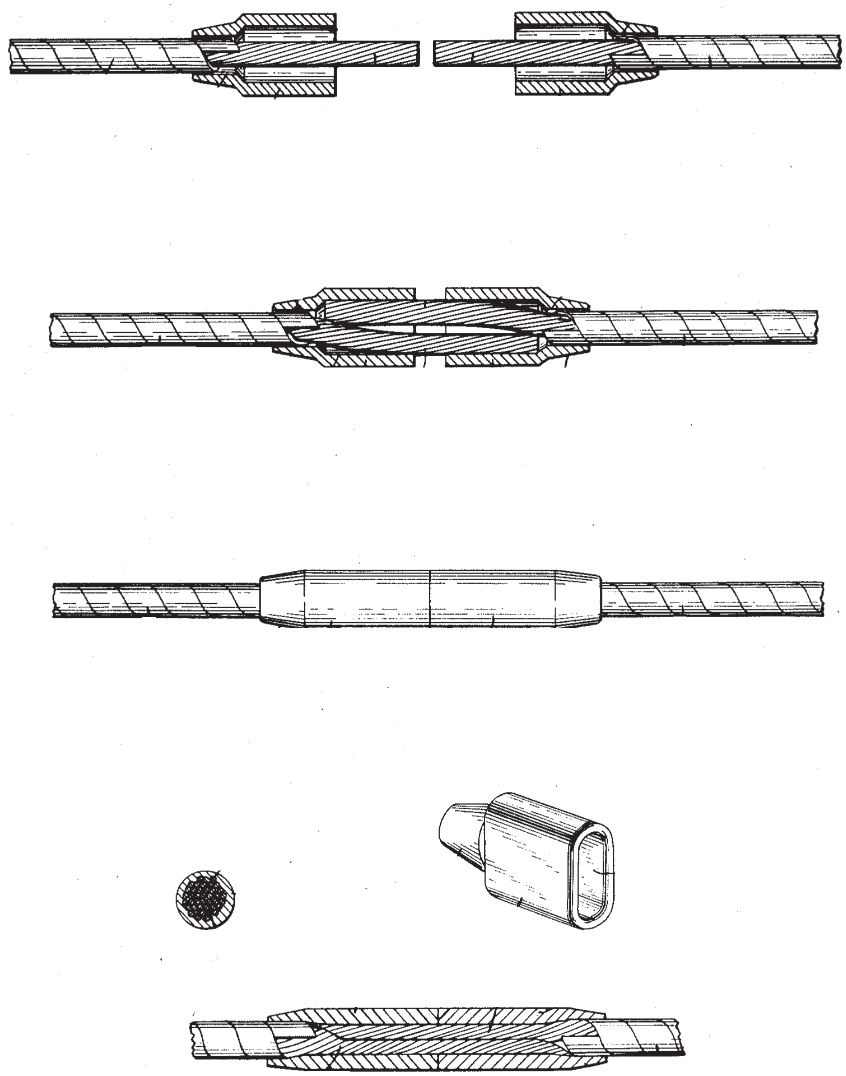


Figure 84. Cable connector (patented product, inventor W.G. Gillmore)

V. Appendices

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