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Department of Civil and Environmental Engineering

A BRIDGE MADE OF COMPOSITE PLASTIC TUBES AND CONCRETE FOR A BASIC ROAD NETWORKS

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Preface

My special thank and acknowledgement go to *Ing. Nicolas Metge*, who gave me the opportunity to intern at the Company ISC. This experience was extremely dense and rich, as I was confronted to many different projects and types of infrastructure. I could also work at a great variety of levels: public tenders, technical expertises, execution studies. This stage answered my personal desires of understanding and entering deeply into subjects. He did not hesitate to give me autonomy and responsibility, and I really appreciated being challenged as I was at ISC. My appreciation also goes to the entire ISC team, always available for explanations, prompt to share their knowledge and willing to learn more.

Special mentions go to *Ing. Patrick Barbier* and *Ing. Riyadh Benosman*, who particularly supported me during these six months and communicated their passion, enthusiasm and know-how.

I would like to express sincere gratitude to *Prof. Ing. Pier Giorgio Malerba* for the time and attention he dedicated to my thesis project. He was sufficiently patient and open-minded to examine the work I suggested. I thank him for sharing his large know-how and experience in civil works and especially his expertise in bridges.

Finally, a large thank you goes to *Ing. Elisa Conti* for her help preparing and setting this work. Its advice has showed very precious for me to understand and answer the expectations of a thesis work in Italia. Her availability and enthusiasm was a constant support during the last months.

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Abstract

The present thesis work takes advantage of the opportunity of a stage, at ISC, a French engineering firm. This company, whose field includes Africa, develops new structural design processes, to adapt to the local context. Hence, the present work aims at developing such a process for a footbridge. Starting from a blank page, requirements include durability of the material, low environmental and economic impact of the structure, simplicity of the process. To fulfil them, the structure shall be light, requiring manhandling elements and no lifting machine. These specifications open two main inter-dependant fields of prospects: the static scheme and the material.

The thesis follows the path opened by a first design attempt made by ISC: a reinforced concrete bridge, cast in PVC tubes. Taking account achievements and limitations of the experience, this thesis develops and expands this intuition, enlarging the use of PVC. First, a different static scheme, that fits better the particularities of PVC, is chosen. The nature of a piping system offers its modularity and container ability, whose interest is weighted in the project framework.

Then, despite the proven interest of PVC for piping systems, the main obstacle to use it in civil engineering is the lack of knowledge the sector has about the mechanical abilities of PVC. Therefore, it is necessary to investigate its types, its modes of production, its characteristics, its reference codes and its structural behaviour of this plastic. Its principal semi-finished derivatives, tubes and fittings, are analysed in terms of geometry and possible implementation.

Once the useful equipment has been presented, several attempts are made before designing the footbridge. Among them, a scale model is realized, to experience and improve the static scheme. Loading test is led and analysed. It helps assessing the structural abilities of PVC piping systems.

To find a correct shape, the study has reaped huge benefits from the use of a parametric algorithm, Grasshopper, combined to a 3D software, Rhinoceros. After parameters are determined, a complete algorithm has been written to model the geometry of the footbridge, and convert it into finite elements thanks to the use of Karamba.

Once the model validated, the works are sequenced. An integral PVC skeleton,

supported by a metallic cable, is built. Reinforcement is disposed before is filled with concrete. The model is calculated under different load cases. Peculiarities of realization are pursued to the very detail of execution studies and normative verifications to European standards.

Originality resides in the structural role given to PVC tubes during concreting phase. This thesis concludes as a matter of fact with the delivery of a ready-to-built footbridge.

Sommario

Il presente lavoro di tesi si avvale della possibilità di uno stage, svoltosi presso lo studio di ingegneria francese ISC. La società, inserita nel contesto di sviluppo dei paesi del continente africano, rivolge la sua attenzione a progetti nuove strutture che si adattino al contesto locale di riferimento. Il presente lavoro, inserendosi in tale contesto, si propone dunque di studiare una passerella pedonale.

Una prima fase è rivolta allo studio dei requisiti quali la durabilità del materiale, il basso impatto ambientale ed economico della struttura, la semplicità del processo di costruzione. Al fine di soddisfare questi criteri, la struttura scelta dovrà essere leggera e composta da soli elementi sufficientemente leggeri per essere trasportati a mano, in modo tale da non richiedere opportune macchine di sollevamento. Tali specifiche aprono lo studio a due principali campi interconnessi tra loro: lo schema statico e il materiale.

La Tesi prende spunto inizialmente da un tentativo di nuovo design progettato da ISC: un ponte in cemento armato, gettato mediante tubi in PVC. Considerando in conto i risultati e le limitazioni di questa nuova idea, il lavoro si sviluppa e espande, ampliando l'utilizzo del PVC come materiale strutturale. In primo luogo viene scelto uno schema statico differente, che si adatti meglio alle peculiarità del PVC. In particolare, la natura del sistema di tubazioni manifesta ottime capacità in termini sia di modularità e sia di involucro, il cui relativo interesse è messo in luce nel contesto del progetto.

Nonostante l'interesse del PVC per i sistemi di tubazioni, la principale difficoltà che si manifesta nel campo dell'ingegneria civile riguarda la mancanza di conoscenza che il settore ha nei confronti delle sue capacità meccaniche. Pertanto, è stato necessario analizzare le diverse tipologie di PVC attualmente in uso, i modi di produzione, le caratteristiche fisiche e meccaniche, così come le normative di riferimento e il suo comportamento strutturale. I principali semilavorati di derivazione, come tubi e raccordi, vengono analizzati dal punto di vista della geometria e della possibilità di attuazione.

Presentato il materiale e i suoi prodotti a disposizione, diversi tentativi relativi allo schema statico sono fatti prima di progettare la passerella. Tra questi occorre citare il modello in scala realizzato ad hoc per sperimentare e migliorare lo schema

statico. Eseguendo una prova di carico è stato inoltre possibile valutare le capacità strutturali dei sistemi di tubazioni in PVC.

Per definire una forma geometrica appropriata, in questo lavoro si è ricorso all'utilizzo di un software Grasshopper basato su un algoritmo parametrico. Una volta determinati i parametri, all'interno del software utilizzato è stato possibile scrivere un algoritmo per modellare la geometria della passerella e successivamente convertirlo in elementi finiti. Infine l'analisi strutturale è stata eseguita mediante l'utilizzo del programma Karamba.

Dopo la validazione del modello, si sono studiate e verificate le diverse fasi del progetto della passerella. Si definisce uno scheletro integrale in PVC, sostenuto da un cavo metallico. Prima del getto viene disposto il rinforzo e riempito con calcestruzzo. Il modello viene analizzato sotto diverse condizioni di carico. Vengono infine definiti i dettagli costruttivi e vengono eseguite le verifiche in accordo agli standard europei.

L'originalità del lavoro risiede nel ruolo strutturale dato a tubi in PVC durante la fase di getto e nella definizione di u progetto di una passerella finalizzata alla sua reale applicazione in paesi in via di sviluppo.

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Chapter 1

Introduction

The thesis work intent is introduced and put into context. The assumptions behind the project developed and the analysis methods for the study of a bridge made of a combination between plastic tubes and concrete are briefly recalled.

1.1 Background

The present work is born from an opportunity that has been given to me: a *French engineering consulting company of the VINCI group*, ISC offered me a stage to develop and expand an ambitious attempt. Working since a few years in *African context* (for example Oyala, tribune présidentielle, pont au Cameroun, Burkina), the firm has been confronted the difficulties that such a context raises:

(a) Materials are far less supplied than in Europe, which makes onerous import often necessary, striving up the costs and the delays;

(b) Road network is not decent, making large zones inaccessible to trucks and cranes;

(c) Most of the workers have no qualification: technological tools and materials shall be avoided.

Moreover, in the sector of construction, environmental issues find a growing resonance, as the necessity to find alternative materials and to integrate the environment in the design process raises.
Therefore, in 2015, with the willing to develop a relevant answer to these acknowledgements, ISC designed a reinforced concrete *footbridge using a permanent formwork made of PVC pipes*. More details are given in Chapter 2 about this project.

1.2 Aim

The first objective of the work was to find the best static *scheme to realize a PVC bridge*, using the parametric algorithm Grasshopper in the Rhino environment, and then to design such a bridge. After analyzing pros and cons of the main different static systems, the footbridge has to answer to a specification note:

- Use of light materials, if possible man-handling, to avoid cranes and lifting machines;
- Use of widespread economical materials, to limit transportation and costs;
- Use of durable material, suited to rustic environment; to avoid maintenance in remote areas;
- Use of material with low environmental impact;
- Span from 15m to 25m, to beat the competition of wooden and aluminium footbridges, for spans up to 10m-12m;

It quickly resulted that the intuition ISC had a year ago was right: I was put in charge of studying the material PVC and enlarging its structural role.

1.3 Approach

The project will be done by support of structural engineers at ISC and in collaboration with the department of architecture who has already tested a method for structurally optimized generative geometry. I have written this thesis parallel with the aim of exploring a structurally informed design process.
The main parametric tool to be used in the project is Grasshopper which is a visual programming editor. As a plug-in for Rhino3D, Grasshopper is integrated with the modelling environment used in e.g. architecture and engineering. Grasshopper offers the opportunity to define precise parametric control over models, the capability to explore generative design work flows and a platform to develop higher-level programming logic by using an intuitive, graphical interface.
For structural evaluation of structures modelled within the parametric design tools Karamba will be used. Karamba is a plug-in for Grasshopper that makes it easy to combine geometric models, finite element calculations and optimization algorithms like Galapagos.
For evaluation of the structural outputs given from Karamba, the limits in terms of internal action and displacements are checked with reference to the Codes (in particular Eurocodes)
Furthermore, the models will focus on the structural and architectural concepts, which are tightly connected. This is likely where the focus on the transdisciplinary collaboration between architecture and engineering will take place.

1.4 Limitations and assumptions

Only linear elastic analysis will be performed, i.e. the calculations are based on the following conditions:

1. Hook's law is valid, i.e. the materials are ideally elastic;
2. Bernoulli's hypothesis that the linear distribution of strain in the cross-section is retained during loading.

Furthermore, Karamba is also limited to linear elastic calculations.

- Only thin plate theory or Kirchhoff theory, i.e. a line that is straight and normal to the mid-surface before loading remains straight and normal to the deformed midsurface. Furthermore, this prohibits transverse shear deformations. (Cook et al., 2002).
- Only three-node triangular element. This is a limitation in Karamba, used FE software integrated with the parametric design tools, that only work with triangulate elements.
- The structures or parts of structures that are analyzed have the same cross-sectional thickness everywhere, i.e. non varying cross-section.
- Buildability or construction method are not investigated in depth. A smaller presentation of this will although be presented for the collaboration project.
- The core plug-ins but not every used plug-ins will be described in detail. This due to that a lot of plug-ins have been used and some of them to a small extent, i.e. small influence on the overall project.
- The most important components in different plug-ins but not all components will be described in detail. For further information about all components for every plug-in the reader is referred to the manual of the program.

1.5 Used Software

The software used in the project are presented in Attachment A. Rhino3D and Grasshopper were predetermined which, in this case, are the foundation of the parametric design tools and consequently the most important tools for e.g. defining geometries. Karamba is also one of the most essential tool in the thesis. It is a well-known FE motor within the parametric design tools.
In particular, the parametric scripts are developed in Grasshopper - Karamba while visualized in Rhinoceros. The scripts are mode of components whose proper in- and out-puts are connected through wires. This creates a very visual way of scripting, not requiring the knowledge of a specific programming language.

1.6 Thesis framework

This thesis deals with the following topics:

- Chapter 2 presents basic concepts that are keystones for the new type of structure.
- Chapter 3 is a state of the art for PVC: reminding the common properties and interests of plastics in general, it shows why PVC is the most pertinent plastic to be used for our scope. Its production processes and classifications are described. Specific mentions of PVC in Codes are referenced. Its mechanical and physical properties as well as its structural behavior are detailed. Project parameters such as its market and main applications are not forgotten.
- In chapter 4, the same methodology as for chapter 3 is applied to semi-finished products derived from PVC: tubes and fittings. The different ways to connect them are analyzed. Influence of their geometry on their load-bearing capacity is studied.
- Chapter 5 is dedicated to a few preliminary attempts to design a PVC footbridge. A scale model has been realized and loaded. Taking into account necessary refinement, a phasing has been proposed to build a full-scale PVC footbridge: it brought to light the impossibility to project a full-PVC bridge and oriented the role of PVC to the role of structural formwork.
- Chapter 6 details materials, loads and supports for the realization of a realistic full-scale PVC concrete composite footbridge.
- Finally, normative verifications according to Eurocodes are made in Chapter 7, for all the materials implemented. The software used to create the parametric FE algorithm of the footbridge are quickly presented. Their inter-operability is briefly described.
- The two Attachments deal with the used software and the drawings of the realized footbridge.

Chapter 2

A Different Way to Realize Structures

In the first part of the work is presented an example of structure that illustrates a new way to realize structures. This structure has a PVC skeleton. That material is well-known and often used for piping systems. It offers the possibility to combine its classical abilities to contain and transport fluids and its mechanical properties, to think out structures differently. Moreover, the building sector is nowadays more and more concerned by social issues, such as green materials, low emissions, durability, recycling, modularity. A promising conception should inspire from these inspiring concepts.

2.1 Modularity concept

The first inspiring concept for this work is *Modularity*. It recalls to the geometrical aspects of the structure considered as a whole. This whole is constituted of initially independent and identified elements, with proper geometry and properties.
The word modular, according to one of its most common acceptation, means part with standardized units or dimensions, as for easy assembly and repair or flexible arrangement and use (Morris *et al.*, 1969). At the same time, according to the Modular Building Institute, a modular construction can be defined as a design and construction process performed in a manufacturing facility which produces building components or modules that are constructed to be transported to a permanent building site.
As a consequence, modularity is very close to the concept of *Prefabrication*, which is the manufacture of whole buildings or components in a factory or casting yard for transportation to the site (Pevsner *et al.*, 1998).

So, first of all, *Modularity* recalls flexibility and ease in the use of the components. It also implies standardization and standard products. In some way, it shifts the difficulty from the execution stage to the production stage: a modular structure is very interesting from the building point of view if its components themselves are easy to find, simple, quick and economical to produce. In other words, modularity has critical prerequisites. Despite its advantages, it is often worth realize the work on site for reasons of implementation rather than prefabricate or provide tailor-made components. As stated above, this concept is at stake for all the different phases of the life of a civil structure: assembly, arrangement, use, reparation, and eventually recycling and deconstruction. Modular construction invokes building a structure with a large quantity of elements but with only a few number of different component. Diversity lies in the use rather than in the nature of the component.

Prefabrication and *Modularity* are already widely spread in architecture and housing construction. Entire houses are indeed nowadays built in factories and either assembled on site or transported as a whole. One of the pioneers of such global prefabrication systems was Raymond Camus [(1)] and its famous so called procédé Camus Delemontey (2007). [(2)] It largely helped to reconstruct the destroyed french cities after the Liberation. When it began to be used in the 1950s, it was very innovating with respect to other processes that were employed: Camus unified and standardized the prefabrication processes for all the components of the building, whereas before, each was realized according to a specific process. Moreover, he integrated all the secondary functions (f.e. pipe networks) to the civil works (concrete slabs). Obviously, it has been largely criticized ever since because of the aesthetic poorness of constructions. Today, this revolutionary system is mainly associated to some sad and gloomy building blocks of the french suburbs.

Prefabrication is of course also used in public works, for example to realize concrete pre-stressed beams. However, for what concerns small pedestrian bridges, as it is the focus of the present work, entire prefabrication processes exist and many companies are able to deliver ready-to-use pedestrian bridges (i.e. Marcanterra, Maadi and Rocla companies).

A. Marcanterra Company

This company produces ready-to-use prefabricated bridges for pedestrian bridges: mixed steel-wood bridges or wooden bridges. They are dimensioned taking into account an $450kg/m^2$ admissible load and a L/400 maximal deflection. In particular:

- *mixed steel-wood bridges* are self-supported, they consist of a metallic frame on which are fixed a wooden plate and mixed steel and wood guard rails. Available spans reach 30m;
- *wooden bridges* are laminated timbers whose spans reach 6-8m for simply supported bridges (depending on the type of bridge) and 30m for arch bridges.

B. Maadi Company

This delivers in every part of the world *poney truss aluminium bridges* designed to the finite elements according to American and Canadian standards, up to 40m-spans.

[(1)] https://www.cairn.info/revue-histoire-urbaine-2007-3-page-15.htm

[(2)] http://materiauxdeconstructiondapresguerre.be/material/heavy-prefab-systems/

(a) Prefabricated bridges by Marcanterra.

(b) Prefabricated bridges by Maadi.

Figure 2.1: Ready-to-use pedestrian bridges.

2.2 Examples of modular structures

Some inspiring modular structures are presented below. More than entering in technical and structural specifications than will be explained later on, the focus will be put on their modular properties: that is what makes them interesting for our scope.

2.2.1 Paper Bridge

The Paper Bridge is a structure designed by famous architect Shigeru Ban and realized in France during the summer 2007 by 27 students, taking part to a workshop, in cooperation with Terrell, a french engineering firm. It is an ephemera arch made of 281 paper tubes, as shown in Fig. 2.2. The Paper bridge has a single span equal to $20m$ and the rise about $6.5\,m$. Paper tubes are assembled into a trussed arch. A bracing system avoids any move and stabilizes the structure. The bridge can bear the weight of 20 people at one time, that is about 1.6 tons.

Figure 2.2: Paper Bridge structure.

The students only used the following components, delivered on site and assemble with simple tooling:

- Paper cylinders, with a diameter $D = 115\,mm$, a thickness $e = 11.9\,mm$ (for a D/e ratio of 10);
- Steel disks (2 by cylinder) with two screw holes;
- Metallic threaded rod;
- Continental net support to assemble the disks;
- Metallic bracing cables.

Steel plates are used to provide rigidity to paper tubes and to ease their connections (Fig. 2.3). They have a double function: one is to allow the paper beams to be pre-stressed, and the second is to connect them. In such way they are similar to equivalent tools for steel frames. Two screws connect them to the support, to restrain their hinge behaviour.

A threaded steel rod is tightened between two plates at each end of the tube so as to provide pre-stressing (Fig. 2.4a) and avoid any boning of the system. Erection is made by a crane thanks to provisional shoring (Fig. 2.4b).

Figure 2.3: Paper Bridge. Details of the connections.

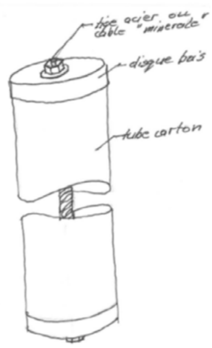
Tubes of internal and external diameters 25cm x 28cm of the same type as those employed by Shigeru Ban have been tested by Terrell (Terrell, 2014) so as to determine the gross mechanical properties of the paper material (values of the Young modulus and of compressive and flexural resisting strengths).
The following orders of magnitude are deduced:

(a) Compressive resisting strength $\sigma_c = 10 - 11\,MPa$;

(b) Flexural resisting strength $\sigma_f = 15 - 16MPa$;

(c) Elastic Modulus $E = 2.1 - 2.2\,GPa$;

(d) Specific weight $\rho = 0.82\,t/m^3$.



(a) Prestressing.

(b) Provisional shoring.

Figure 2.4: Paper Bridge details.

Closing remarks. Theses values place the type of paper that Shigeru Ban employed in the category of the *poor construction materials*. Nevertheless, they allow it to be used for structural applications. The use of paper raise obvious *durability questions*, despite applied costly and time-spending protective treatments:

it remains a non-durable material in exterior environments.
Shigeru Ban bypassed the main structural problem - connections - thanks to a steel frame method. But the final result quite sophisticated. Therefore setting it up takes a long time. Moreover, such a solution adds a considerable weight of steel to the structure. Consequently, the component of the Paper Bridge are not as standard as they were meant to. They had to be proceeded, even if can not be inferred that they are custom-made.

As a conclusion, coming back on the concept of *Modularity*, the Paper Bridge components allow for *flexibility*, they have standardized dimensions. Elements of *few different natures* were used in large quantities. Though, they are not so standard nor easy to find. Finally, erection is not very rapid. Even if this bridge has never come to a commercial scope because of these drawbacks, its modular conception is interesting. Shigeru Ban introduced a *new material* for structural applications. The structures satisfies the spirit of simplicity and ease. Ulterior problems of durability made design become more complex.

2.2.2 Facade of the EcoArk pavilion

The EcoArk pavilion, in Taïwan, was built by the Taiwanese conglomerate Far Eastern Group in 2010. The element of interest for our scope is the façade (Fig. 2.5a): it is made of 480000 Polli-Brick (100% PET bricks) (Fig. 2.5b), which are realized thanks to 1.52 million plastic bottles [3]. Although its structure is a classical steel frame traditionally built, the façade is entirely modular. Thanks to its original design, the EcoArk façade weights 1/5 of traditional façades.
The building has a length about $130\,m$, its height is $20\,m$ and it is made by 9 floors. The ground area covers approximately $4300\,m^2$. As often for expositions (f.e. Expo2015 in Milan), the pavilion is thought to be quickly built, deconstructed and then reconstructed elsewhere.

(a) Façade. **(b)** Polli-brick elements.

Figure 2.5: Chracteristics of EcoArk pavilion

For what concerns the Pollibrick panels (Fig. 2.6), the main details are summarized

[3] `http://www.miniwiz.com/miniwiz/en/projects/archi/ecoark`

in the following:

- Area of one panel: $2.85\,m^2$ (162 x 76 x 38.5 cm thickness);
- Weight: $63\,kg$ (that is $57\,kg/m^3$ or $22\,kg/m^2$);
- Resistance: Wind pressures of $3.3\,kPa$ and loads q of $345\,kg/m^2$, which represents a q/g ratio major than 15.

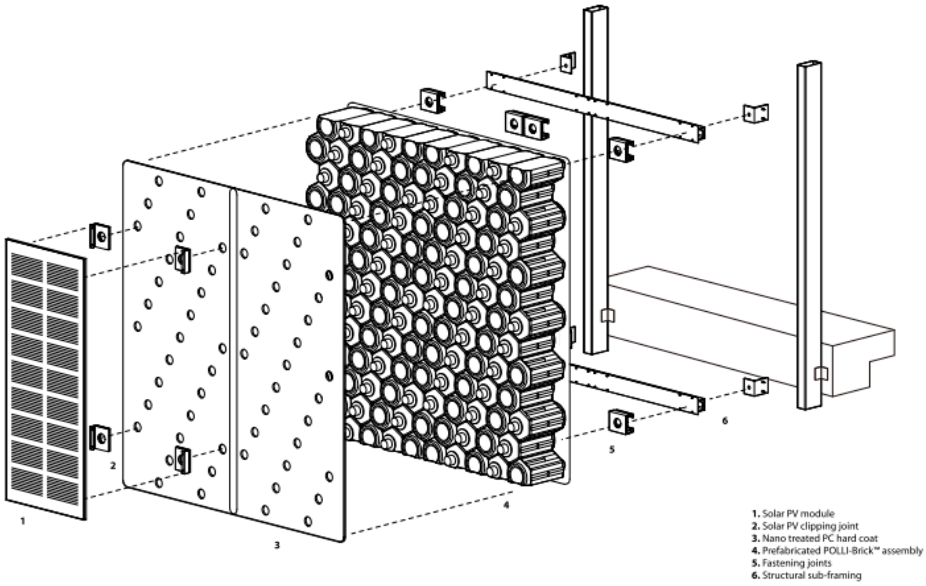


Figure 2.6: Detail of a Polli-Brick panel.

Modular structures can as a matter of fact achieve great results in terms of resistance. The ratio between the admissible load and the weight by unit area is really high. It demonstrates the mechanical properties of widespread and common plastics if they are wisely used.
From left to right, the façade is constituted of :

1. A solar PV module;
2. Solar clipping joints;
3. Nano-treated PC hard coat;
4. Prefabricated Polli-Brick assembly;
5. Fastening joints;
6. A structural sub-framing.

Closing remarks. Such pollibrick plastics offer moreover the great advantage to be *recyclable*. At the same time *Modularity* is thus a hefty argument, as it offers facility and rapidity of supply and erection. For the façade of the EcoArk, *facility*, *simplicity*, *rapidity* and *economy* requirements are satisfied in the execution. But its components are quite sophisticated.

2.2.3 Make-A-Bridge system

The Make-A-Bridge system (Fig. 2.7) is a kit developed by the north American engineering and design firm Maadi, specialized in structural aluminium applications. This company often delivers ready-to-set-up structures like pedestrian bridges. The design is done without any welding. Transportation is ensured even in most remote areas. Only a small crane ($1.6\,t$) is required. Setting it up is very fast: it can be done by 3 people in 5 hours. Available spans go up to $18.3\,m$, for $0.9\,m$ and $1.8\,m$ widths.
The pedestrian bridges delivered by Maadi have the following characteristics:

- Self-weight: $44 - 73\,kg/m^2$, depending on the components arrangement and on the type of footbridge;

- Admissible variable load: for golf car is $240\,kg/m^2$ or $480\,kg/m^2$;

- Maximal deflections: from L/500 to L/240.

The ratio q/g varies between 3 and 11: modularity has been demonstrated again a mean to design light structures and to increase significantly the part of self-weight in the total loads to bear.

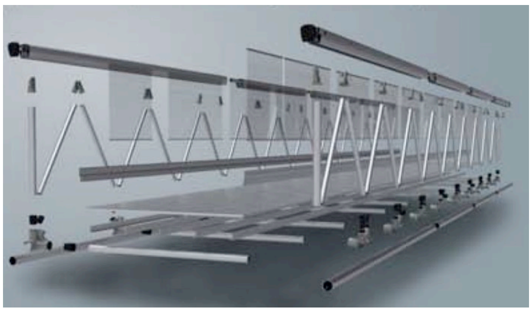


Figure 2.7: Components of a Make-A-Bridge kit.

The commercial documentation on Fig. 2.8 presents the limits of use for the Make-A-Bridge system depending on their width, span, expected loading (on the left: bicycles, pedestrian and lightweight vehicles; on the right: pedestrian and lightweight vehicles [(4)]).
In addition, for these types of bridges a fatigue tests have been performed. A $0.61\,m$ width and $6.1\,m$ length Make-A-Bridge model (the corresponding area is $3.72\,m^2$) is loaded in 3 points, according to Fig 2.9. As an order of magnitude, the uniform

[(4)] The expression *Lightweight vehicles* is meant for example for small golf cars

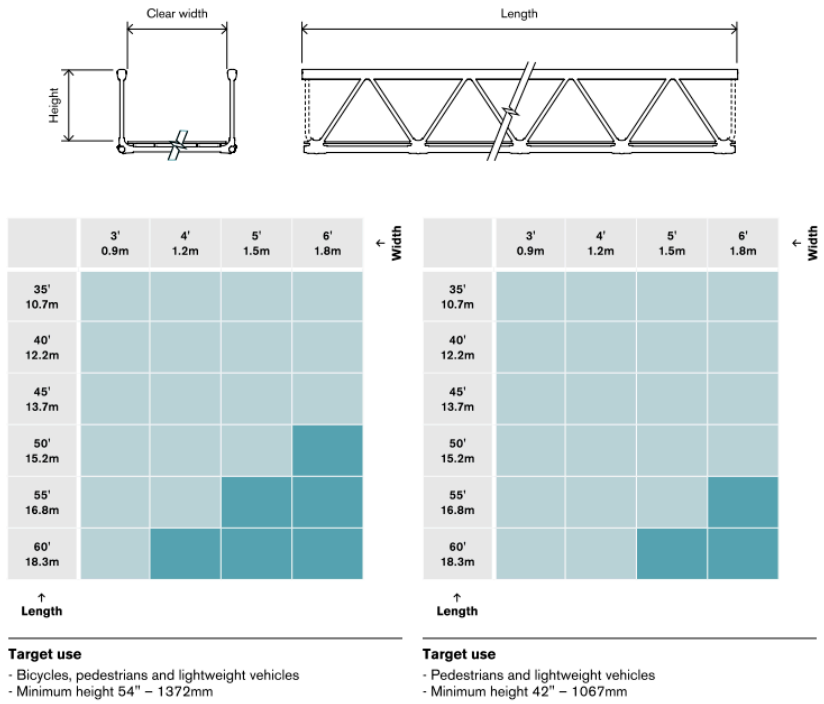


Figure 2.8: Domains of utilization for Make-A-Bridge solution.

maximal admissible load is:

$$Q_{tot}^{max} = 4.8\,kPa \cdot 3.72\,m^2 = 1.8\,t$$

In similar way, it weight approximately is:

$$G_{tot} = 44 - 73\,kg/m^2 \cdot 3.72\,m^2 = 165 - 270\,kg$$

The model bends of 6.1 mm under a total load of 14 t (elastic limit), which is 8 times the uniform maximal admissible load. Ultimate force is 18.3 t, which is about 100 times the weight of the structure.

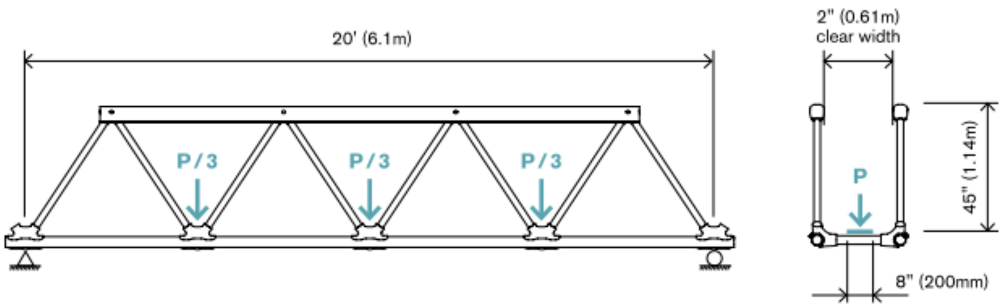


Figure 2.9: Failure test scheme.

In the end, Maadi is a skilled company in the use of aluminium for structural application. So, it is useful to recall the role of aluminium as a construction material. In fact, Aluminium would be a very serious contender of steel for what regards structural applications if its price was not so high: indeed it is often twice as expensive as steel. Here is presented a short comparison of steel and aluminium about some important design values: respective resisting - tensile - strength, Young modulus and specific weight and gross price for civil works supply. As both steel and aluminium for construction are alloys, the table only contains ranges and orders of magnitude.

Characteristics		**Steel**	**Aluminium**
Price	[€/kg]	0.5 - 1	1 - 2
Strength	[MPa]	250 - 1500	200 - 500
Young Modulus	[GPa]	200	70
Specific Weight	[kg/m^3]	7.8	2.6 - 2.8

Table 2.1: Comparison of steel and aluminium characteristics.

As shown in Tab. 2.1, even if the mechanical properties of steel are better for structural applications (between 1.5 and 3 times higher than for aluminium), it is 3 times as heavy as aluminium. That's why aluminium is more and more used in applications for which lightness is crucial. Speaking of bridges, this fact is significant as self-weight is often the main load to carry. Therefore, a reduction of self-weight could potentially be accompanied by the use of a weaker material.

Closing remarks. As matter of fact, the Make-A-Bridge system constitutes a *robust footbridge*. It is besides an efficient solution, as it is very *simple*, *light*, *easy* to deliver and to set up, in a word *accessible*. Thus it became a competitive footbridge for small ranges (lesser than 20 m). Its components are basic, even if they are custom-made for this application. It demonstrates the feasibility, interest and competitiveness than *modularity* can find for bridge applications.

2.3 Formwork concept

In this section, we focus on the specific nature of the elements that this documents aims to propose as structural elements: tubes or tubular shapes. Despite the most well-known and widespread domain of use of tubes is fluid transportation, resisting to the internal pressure may be assumed their only structural role. A wide range of tubes cover this scope. Further details will be given in Chapter 3. Basically, a tube is first and foremost a container: it contains - in general - a fluid (gas, air, water, oil). According to this, it could have the use of creating a sort of formwork system. According to a famous English dictionary (Simpson and Weiner, 1989), a *formwork* is an arrangement of wooden boards, bolts, etc, used to shape reinforced concrete while it is setting. On the contrary a scientific dictionary (Parker, 1984) insists in its definition on the notion of temporariness; it means a temporary wooden casing used to contain concrete during its placing and hardening. Whereas for a famous American dictionary (Morris *et al.*, 1969), a formwork is not necessarily a wooden structure. It simply is the structure of boards that make up a form for pouring concrete in construction. A crucial element dealing with *formworks*, which appears transparently from the word itself, is the word form: a formwork makes up a form for concrete, it acts as a mold, a cast. Not only a formwork shapes the final structure. It is concrete container; it prevents it from pouring away. The use of formwork is inseparable from the use of concrete.

That being said, the most used and widespread formworks are currently made of wooden plates, bolt and supported to resist the thrust of liquid concrete, as shown on Fig. 2.10.

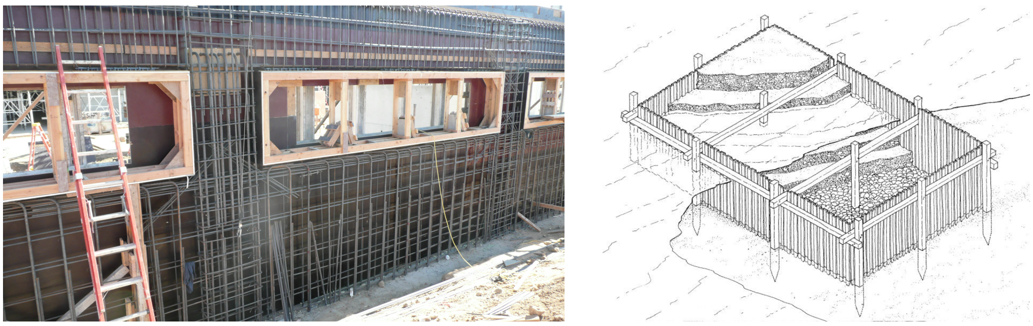


Figure 2.10: Examples of wooden formworks.

For every concrete elements, casting is the critical step for many reasons:

- Firstly beacuse it lasts a long period, in general 28 days, which is necessary duration for concrete to harden and be able to resist loads;

- Then because, whereas before casting any modification or adaptation can be made to structure, once casting is finished, prior orientation or decision is endorsed and definitive. Any change would involve destructing the new reinforced concrete structure or element;

- Next, because casting needs a lot of preparation: it involves manpower, time, money, and materials. The casting material is reused as much as possible to limit the budgetary impact of this step: in this case we deal with *re-usable formworks*. On the contrary, they are called *lost formworks*. The amount of preparation that casting requires increases with the complexity and originality of the concrete element to cast; casting a rectangular slab is quite easy, because it is a simple geometrical form, whereas casting a double curvature wall is much more requiring, because the desired form has to be a custom-made created footprint; what's more it is executed with rectangular standard plates. Therefore one always tries whenever possible to take advantage of existing structure or surface to become natural formworks.

Many different types of formworks exist. For our scope, the review will focus on the modular and the tubular ones.

2.4 Examples of formworks

Some types of formworks with their properties are now presented and taken into cosideration, in order to underline which kind of elements cover a structural role during the casting of concrete.

2.4.1 Geotube panels

Geotube are principle of re-usable plastic panels to cast rectangular or square reinforced concrete columns or beams (Fig. 2.11a). They are made of nylon, treated against UV radii. The two complementary part fit together to create a waterproof mold. They are obviously modular, as the system is based on assembling as many elementary parts as needed. Different dimensions are available to adapt different columns. As a matter of fact, the design dimensions have to fit which available width, so as not to overbuild the structure. Moreover, they are more than 100 times re-usable, easy to use thanks to the presence of handles, and allow for rapidity and precision in their setting up. However, it demonstrates a drawback of modular systems: they only adapt to a discrete range of situations, which correspond the available dimensions.

(a) Plastic panel.

(b) KAP formworks.

Figure 2.11: Use of different formworks for casting columns.

2.4.2 Lost formworks

The french company Accessbat commercializes lost formworks for columns. Their formworks are made of KAP material [5]. It is a composite light and resisting material which allows to cast as much as $4\,m$ high at once. Such KAP formwork (Fig. 2.12) are therefore able to resist the internal pressure generated by a $4\,m$ height of concrete:

$$p_{int} = \gamma_c \cdot H = 2.4\,kN/m^3 \cdot 4\,m = 9.6\,kN/m^2 = 9.6\,kPa$$

Available diameters vary by 50 mm from 150 mm to 600 mm. Obviously, the cylinders are impermeable, and demoulding is possible thanks to an helical metallic wire. These formworks also exist for rectangular and less conventional sections of columns.

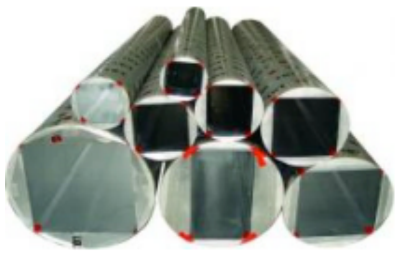


Figure 2.12: Unconventional forms of KAP formworks

2.4.3 Spacing tubes

The main reference for plastic casting tools are spacing tubes, which are PVC crosspieces. They are used to cast in situ the threaded metallic rods that maintain the correct spacing between wall formworks submitted to concrete lateral thrust. Plastic nozzles allow to seal the ends. Available diameters are (int x ext) 22 x 26 mm or 26 x 32 mm. They will then be lost in concrete when the metallic rod is removed and re-used.

Figure 2.13: Spacing tubes with corresponding nozzles.

Closing remarks. Plastics are more and more used to cast concrete as they allow *waterproofing*, *flexibility* and *modularity* on site. Among them, plastic tubes are about the major part. Modular formworks have already permitted to facilitate concrete casting and reduce its cost. Tubular formworks are very handy. They indeed join together both:

[5] Acronym for Kraft, Aluminium, Paper

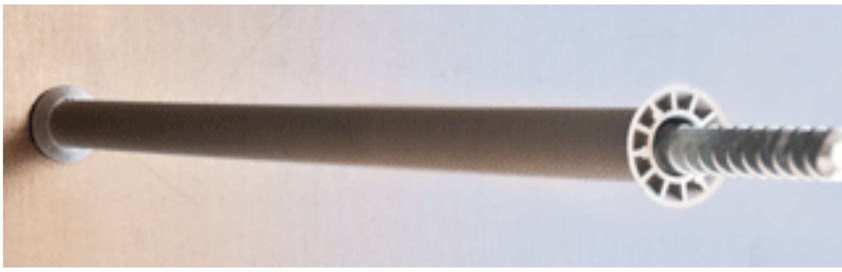


Figure 2.14: Spacing tubes containing a metallic threaded rod.

- the possibility to contain a fluid like liquid concrete;

- the ability to resist well internal pressure, especially concrete pressure for vertical members.

A great domain of prospective would ally the concepts of *tubularity*, *formwork* and *modularity* to quickly create and set up a formwork network in which concrete would flow to fill at once the entire structure.

2.5 Case Study. An existing particular pedestrian bridge

Starting from the concepts previously explained, a special focus is hold on an existing pedestrian bridge realized in 2015 by a company named ISC, an engineering firm of the French group Vinci. Its main peculiarity is the use of PVC tubes as a lost formwork to ensure the casting of reinforced concrete and to led a more efficient design. The project and its main characteristics and information of interest are detailed below. It is necessary to state that this work is a prototype. At the same time it forces its way in evaluating the possibility to associate a structural role for PVC formwork.

2.5.1 Presentation of the project

The project was based on the belief that the main barrier to the realization of reinforced concrete trusses is casting. Even if a truss is usually one of the most efficient and material saving solution, this step would actually be too demanding and difficult if compared to the realization of an equivalent plain reinforced concrete beam. And reinforced concrete trusses references are indeed quite tough to find.
This is especially true for what concerns short-span bridges (minor than 30m): at this point, the trade-off between the casting cost and the relative ease to cross such distance is always unfavourable to concrete trusses. One should always prefer using prefabricated pre-stressed concrete beams.
The underpinning key-idea of the project itself was the inspiration to use classical PVC tubes (for evacuation) as a *lost formwork* to make a reinforced concrete truss become competitive against other pedestrian bridges solutions, like prefabricated

delivered concrete or aluminium bridges, or aluminium kits (f.e. Maadi, as described in Ch. 2.2.3).
PVC tubes and their connection system (as described in Chapter 3) are indeed by nature a waterproof modular system. They are designed to welcome quite pressurized fluids. At this point, formwork is not a problem anymore because no particular effort should be spent on :

1. connecting the basic formwork elements;
2. realizing the particular shape;
3. ensuring the sealing.

2.5.2 Requirements

The company ISC gave itself a specification notes for the project. The main requirements for this challenge in the design are:

- Durability;
- Simple set up: composed of light materials, to ease its implementation and shall not need any lifting machine;
- Simple statical scheme: to be implemented even by unqualified workers;
- Low cost: materials will be cheap and sufficiently available to limit transportation and costs;
- Adaptability: referring to rustic environment.

2.5.3 Peculiarities

This paragraph details particular design features of the project and practical decisions that were made necessary, even against the original spirit:

(a) The only shaping elements are plastic tubes and connections (Fig. 2.15);

(b) Reinforcing bars are placed in the PVC tubes (Fig. 2.16);

(c) Self-compacting concrete has been used to make it flow more easily in the congested formwork (Fig. 2.17). In particular, concrete is poured thanks to plastic awnings into 6 holes, distributed at the top of the truss, so as it flows directly in the diagonals. Concreting is helped by the presence of shoring facilities. PVC tubes have been broken at some points to check the aspect of the concrete. It resulted to have hardened well, despite the unavoidable presence of small air bubbles trapped between the tube and the concrete;

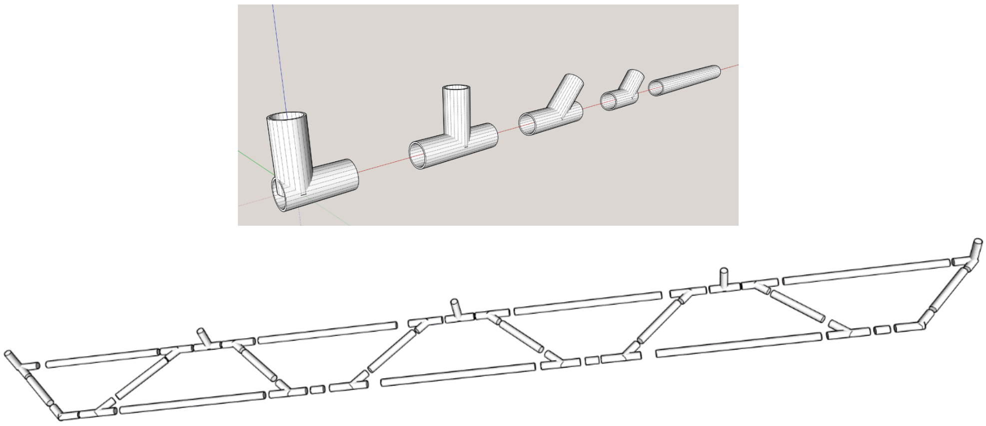


Figure 2.15: Model of plastic connections and plastic skeleton.

Figure 2.16: Disposition of the reinforcing bars in the plastic sections.

(d) Tightening of half-shells to ensure sealing (Fig. 2.18a). In fact PVC connections had to be sliced into two half-shells so as to let reinforcing bars overlap and to allow their fastening. Metallic hose clamps are used to tighten the half-shells and avoid any concrete leak during pouring;

(e) Setting up on supports necessitated a mobile crane and a strap system (Fig. 2.18b).

2.5.4 Geometrical Chracteristics

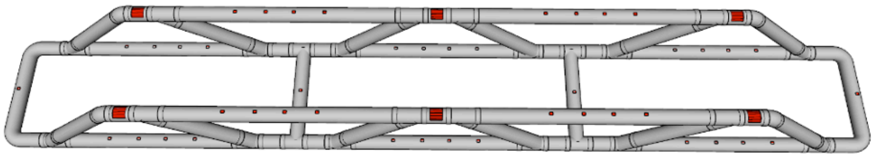
The dimensions of the pedestrian footbridge are summarized in Tab. 2.2.
Two different materials compose the section, that is uniform for any component of the truss:

- PVC tubes, diameter Φ 200 mm, thickness 4.9 mm ;
- Concrete C25/30 constitutes the interior section, diameter Φ 190.2 mm.

2.5.5 Loads

Pre-Designing was done taking into account the following loads:

(a) Concreting step.



(b) Position of concreting holes.

(c) Satisfying aspect of concrete once hardened and deshuttered.

Figure 2.17: Concrete peculiarities.

- Self-weight of concrete (as permanent load): g;
- Pedestrian uniform load (as variable load): $q = 500$ kg/m^2 (according to (Eurocode, 1991)).

As a tube has an interior diameter D_i such as:

$$D_i = D_e - 2 \cdot e \tag{2.1}$$

where e is the tube thickness (4.9 mm) and D_e is the exterior diameter (200 mm). Assuming for the reinforced concrete a specific weight $\rho = 2.5$ t/m^3 and computing the internal concrete area A_i, the permanent load is given by:

$$\begin{aligned} A_i &= \frac{\pi}{4} D_i^2 \\ g &= \rho A_i \end{aligned} \tag{2.2}$$

(a) Tightening hose clamps. **(b)** Setting up of the pedestrian bridge on supports.

Figure 2.18: Practical decisions.

Data			
Width	w	1.00	m
Height	H	1.20	m
Span	l	11.00	m
Overall length	L	12.00	m

Table 2.2: Pedestrian Bridge Data

2.5.6 Calculation

So as to resolve quickly the truss, calculation was done by ISC team with the finite element software *Graitec Advance Design* [(6)], performing a linear elastic analysis. Supports are placed at 50 cm of each end of the bridge, so as to get a 11 m span out of the 12 m length bridge.

2.5.7 Results of the analysis

Axial Forces. As expected because of the horizontal shape of the truss, highest normal stresses are around midspan, where bending moments are maxima. As it can be seen in Fig. 2.19a, the maximum axial force F_{max} is:

$$F_{max} = \pm 12.5 \text{ t} = \pm 125 \text{ kN}$$

[(6)] Graitec Advance Design is a software for structural analysis and design of Reinforced Concrete, Steel and Timber structures according to the latest versions of Eurocodes (EC0, EC1, EC2, EC3, EC5 and EC8), North American (ACI-AISC) codes and Canadian codes(A23.3, S16). `http://www.graitec.com/it/ad.asp`

The corresponding normal stress in concrete is:

$$\sigma^N_{max} = \frac{F_{max}}{A} \qquad (2.3)$$
$$\sigma^N_{max} = 4.4\,MPa$$

which is far below the resisting strength of a C25/30 concrete.

Bending Moments. ISC team did not manage to design a perfect truss because of compatibility problem between plastic tube connections. Further explanations and details on this will be given in Chapter 3. The fact is that the non-optimal truss, with subsequent eccentricities at nodes - truss members do not strictly converge to one node - engenders parasite bending moments in the members, as shown in Fig. 2.19b.
Maximal calculated bending moments are around:

$$\text{M}_{max} = \pm 14.3 \text{ kN.m}$$

They are located, as a logical expectation, at the level of the nodes. Subsequent bending stress is computed as:

$$W = \frac{\pi.D^3}{32} \qquad (2.4)$$

$$\sigma^b_{max} = \pm\frac{M_{max}}{W} \qquad (2.5)$$

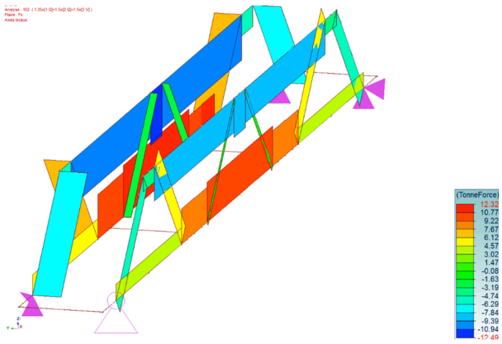
Therefore, neglecting the shear contribution to stress, bending contribution to stress writes as:

$$\sigma^b_{max} = \pm 21.2 \text{ MPa}$$

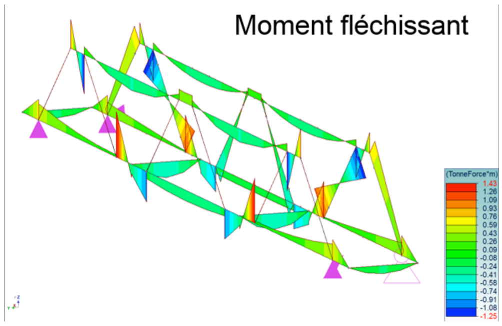
This contribution is far from negligible. It contributed to the need of a non-linear classical reinforced concrete computation that, taking into account that maximal axial forces and bending moments are not collocated, allowed to check the sections and the structure.
As this short calculation showed, the effects of non-optimality of a truss for compatibility reasons are tremendous. They clearly overweight the first order analysis and become themselves critical.

Deflection. The FE element software also allowed for a rapid calculation of the midspan maximal deflection. As showed in Fig. 2.19c, at ULS maximal deflection occurs at midspan and equals 8.5mm. This is highly satisfying as, for a 11m-span it stands far above the most critical deflection criteria:

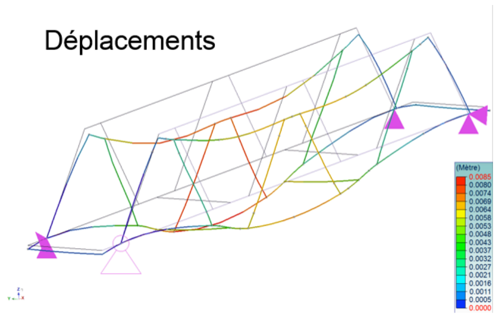
$$\frac{L}{1300} \gg \frac{L}{500}$$



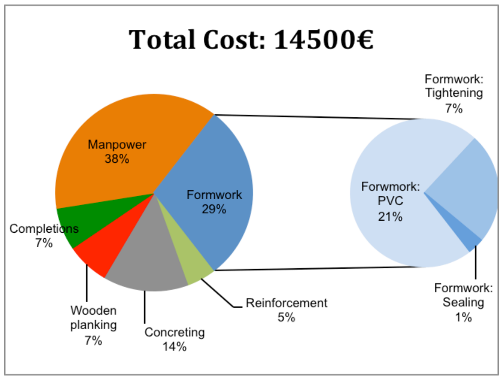
(a) Axial Forces.



(b) Bengind Moments.



(c) Displacements.



(d) Repartition of costs.

Figure 2.19: Pedestrian Bridge results.

2.5.8 Analysis of the costs

An important factor to evaluate the relevance of a statical scheme is the total cost of its production. For the studied structure, the costs of the different tasks are classified and detailed in Fig. 2.19d. The repartition is such that the total cost is divided according to:

- Formwork: it regroups the gross material (plastic tubes and connections), its sealing (with a specific plastic seal) and tightening.

- Manpower: the cost of manpower for every task is included in this task.

- Concreting: includes the concrete material, its delivery on site and diverse small equipment.

- Reinforcement: this embraces the price of steel reinforcing bars.

- Completions: contains the price of the crane to install the footbridge from the shoring to the definitive supports.

- Wooden planking.

Total costs equal 14500€. Taking into account that the bridge is 1 m wide and 12 m long, the price by unit of area is 1208€/m^2. This is a quite elevated ratio, as prefabricated pre-stressed concrete bridge are available for 800€/m^2. However, this number deserves a discussion.

As it has been said before, this work is a prototype: as such, it required certain unavoidable part of testing and thinking on site. Moreover, several solutions to resolve sealing and reinforcement problems have been tested, and discarded. As a consequence, the indicated total costs are obviously over-estimated with respect to a well designed process. Formwork stands for a important part of the total cost (29%) especially because of PVC connections (21%). As it will be explained in the next chapter, their price is exponential of the nominal diameter. Then, 8% (1160€) of the total price has been spent to recreate a sealing (plastic seal and tightening metallic hose clamps), because the arrangement of the reinforcing bars make it necessary to cut the connections.
It is worth notice that PVC materials costs more than concrete and steel structural components together (21% vs 14% & 5% respectively).
The final displacement of the structure after concreting and hardening costed up to 7% of total cost ($\sim$ 1000€).
A great amount of manpower has been needed because of what was said previously: it is difficult though to evaluate the part that one could save. Though, avoiding the cut of the connections and realize a cast-on-site operation would save more than 20% of the total cost, because manpower would also be reduced. As a matter of fact, it would induce a reduction of price by unit of area ratio to around 960€/m^2, which is sufficiently low to be taken into account, given the advantages such a process offers incidentally.

2.5.9 Disadvantages and Limits

The main limits of the project are summarized here:

1. Necessity to employ a crane after hardening;
   As the structure had been erected on a provisional planking, the process needed a crane to move the footbridge to its final position. A great font of economy and rapidity would be to erect the PVC skeleton on the definitive support with provisional shoring if necessary and to pour concrete directly into it. Once concrete has hardened, only the provisional shoring would need to be dismantled.

2. Density of reinforcement at the nodes (Fig. 2.21);
   It is due to a non-optimal design of the truss causing parasite moments.

3. Complexity of subsequent sealing;
   It needs to be sealed with liquid seal and metallic hose clamps.

4. Geometrical compatibility between PVC connections;

Figure 2.20: The structure is moved to its definitive support once concrete has hardened.

Figure 2.21: Density of reinforcement.

As explained in the next chapter, PVC connections are only available for a few numbers of angles (67°30, 87°30, 45°) which links the height and the length of the footbridge to the number of horizontal subdivisions.

Figure 2.22: Liquid seal to avoid concrete leaks.

2.6 Concluding Remarks

Table 2.3 summarizes the main advantages and drawbacks or lacks of a modular structure. It has already be detailed why a modular structure was, in general, *simple, easy, economical, rapid* - in a word: *smart* - to set up.
But, in general, it can't be hidden that they lack *aestheticism*. Indeed, they are not designed in that scope. This is not their specific focus. Design are often basic and above all studied to be performing. Even though the same components can be used for different modular systems.
Depending on the material, they can be as robust as that an equivalent non-modular structure. Their lightweight often make them *more efficient*.
The question of their *adaptability* depends on the context: the design of such structures is completely adaptable because it only depends on assembling components. But, once the design is validated and the works have started, they give birth to quite rigid structures, because of the need of compatibility the diverse elements require.

Advantages	**Drawbacks**
Simplicity	Aesthetics
Facility	Importance of the choice
Diversity	of the material
Adaptability of design	Adaptability on site
Rapidity	Appropriate/Custom-made
Economy	components
	Not Custom-made structures

Table 2.3: Pros and cons of modular structure.

One could have thought that using PVC tubes and their appropriate connections would have led to a more efficient design. But, problems occur with reinforcement. As it is means to deal with tensile concrete, another solution is to avoid concrete to be under tension. Therefore a further improvement could lie in a pre-stressing phenomenon in concrete members.
Geometrical compatibility problems of the piping system have raised from this project. Again, this demonstrates the drawbacks of modular systems when it comes to refinement: a wide range of solutions exist, but this range is discrete.
However, that being said, the casting of the reinforced concrete footbridge demonstrates the possibility to use plastic tubes to cast concrete. A certain number of problems has to be solved at this point so as this solution to become really interesting from a practical point of view.

A further improvement would be to *make this modular tubular formwork able to carry to the concrete weight*, until it has hardened so as to install it very quickly on site on its supports and then pour concrete into it. It would not need any lifting equipment and would limit the provided that the previous remarks are taken into account. *Determine whether this is possible is the task of the present work.* This amounts to giving a structural role to the formwork in question.

As a consequence, the problematic is about the possibility to build efficiently a safe and robust concrete structure with a formwork having the following characteristics:

- structural role;
- tubular form and resistance;
- modular conception.

Chapter 3

PVC: a material for civil engineering

The objective of this chapter is to demonstrate that PVC is a pertinent structural material for civil engineering applications. Reminding that PVC is part of the family of plastics, an overview of the material is proposed as it is necessary to fix why it is interesting to our purpose. Its physical and mechanical characteristics will be detailed, as well as its production, use and parameters. Then description will move on the semi-finished products that derive from it: different types of pipes, connections, and auxiliary elements.

3.1 Family of plastics

After the nineteenth century, the use and production of plastics were still in their infancy. Current modern plastics have only seen their first developments between 1920 and 1940. During this period were invented f.e polyvinyl chloride, low density polyethylene, polystyrene, and polymethyl methacrylate. The advent of the Second World War increased steadily the demand, mainly to substitute for materials in short supply, such as natural rubber. Large-scale production after the war combined to the founding of new types of plastics reduced dramatically their cost and allowed it to compete with classical material, such as wood, metal, leather, glass. Nowadays, they greatly contribute to reduce weight and prices of industrial products and to increase energy efficiency.
In the 2010s, there are more than 90 generic classes of plastics. These classes can be then split into 1000 sub-generic variants. Finally, plastics exist under more than 50,000 commercial denominations. Therefore, it is necessary to fix what is intended by the word *Plastics* and which category this work will deal with.
Among the great diversity of definitions of the word plastic, we will agree on the definition of the Collins English Dictionary (Collins, 2004): any one of a large number of synthetic usually organic materials that have a polymeric structure and can be moulded when soft and then set.
Therefore, all plastic materials have a polymeric structureare, which means that

they are polymers [1]. Again, the use of a dictionary enlightens the meaning of this word: any of numerous natural and synthetic compounds of usually high molecular weight consisting of up to millions of repeated linked units, each a relatively light and simple molecule.
This reminds the definition of the word modular. Polymers are very long chains of molecules linked between them. These molecules are called monomers. The characteristics of the polymers will result from their atomic structure and chain composition, that can include cross-linked chains (reticulation) and other types of monomers (co-polymerization).
They have a synthetic origin, which means that they result of an artificial process invented by humans, in contrast to natural polymers such as proteins. Then, all plastics come from organic materials, among which first and foremost: oil. From this ensues a full range of common properties.
Finally, and most important for our scope here, they can be moulded when soft and then set. This is what often confuses because it is the definition of "‘having plastic properties"’, as dealing with art or mechanics[2] (ductility of a material). Plastic have a common feature with concrete: the first part of their life is carried out in a soft form, and the second in a solid and tight form.
The next part develops the common factors affecting the behaviour of plastics.

3.2 Generalities on Plastics Properties

Generally, plastics have in common the following properties (Lecomte-Beckers, 2015):

- a relatively good resistance to chemical agents. This property actually depends heavily on the type of plastic and chemical;
- an easy shaping;
- notch sensitivity;
- a low specific weight. A short comparison of densities for classical construction materials is presented in the Tab. 3.1;
- sensitivity to cracking. Like concrete, plastics are susceptible to crack. Two different cracking are distinguished:
  1. *Stress Corrosion Cracking* (SCC). The vulnerability to cracking is measured before and after immersion by loadings of a sample;
  2. *Environmental Stress Cracking* (ESC). ESC takes into account the simultaneous actions of stress and environmental actions.

[1] From the Greek polumeros: *consisting of many parts*, formed of polu-, *poly-* & meros, *part*
[2] Actually, *Plasticity* is a state that materials can reach: they may then support additional strains without significant reaction forces. In other words, they are softer, more deformable.

Materials	**Density** $[g/cm^3]$
Steel	7.8
Stone	2.7 - 3
Aluminium	2.7
Glass	2.5
Concrete	2.4
Masonry	2
Plastics	0.9 - 2
Wood	0.4 - 1.2

Table 3.1: Comparison of specific weights of different construction materials.

- (quite) weak mechanical properties - except for composites - relatively to other construction materials;
- a temperature-limited behaviour, and thermodynamic effects;
- a visco-elastic behaviour.

In general, provided data sheets show short-term properties. They do not take into account temperature, stress, time and environment effects. Yet, engineering design can not ignore these factors. This is all the difficulty of converting theoretical properties into design data: such a challenge will be faced in section 3.5 and followings.

As an example, limit strain ϵ_y from regular tests and data sheets is often greater than 20% or even 50%, which means a 1m-long plastic profile sample could support stretching up to 20 cm or 50 cm. Chris O'Connor, from the consultancy company Smithers Rapra, which has developed an expertise in plastics (Booth and Robb, 1968), prescribes not to overpass severe limits for engineering purposes: its recommendations are shown in Tab. 3.2. As a reference, for concrete, strain limits at Ultimate Limit State (ULS) ϵ_{cu} are around 0.25% - 0.35%(3). For steel, ϵ_{uk} rise up to 2.5% or 7.5%(3).(4) Consequently, plastic have similar strain limit to concrete (Tab. 3.2).

State of polymer	Static Stress Conditions	Cyclic Stress Conditions
Amorphous	0.5%	0.3%
Crystalline	0.8%	0.5%

Table 3.2: Suggestions of strain limits of plastics for engineering purposes.

In addtion, the family of plastics presents a very wide range of mechanical properties: tensile strength is comprised between 20 MPa and 800 MPa and Young modulus between 1 GPa and 100 GPa. Indeed, the elastic limit of a polymer depends on:

(4) Depending on the type of concrete/steel, and on the type of model for the stress-strain relationship.

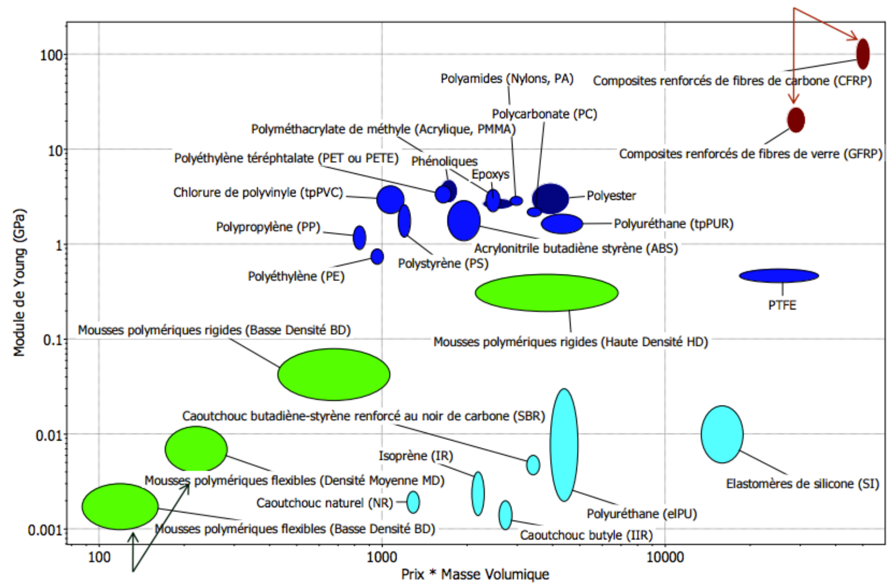


Figure 3.1: Variation of Young modulus according to a specific weight-and price growing function.

1. the nature of the polymeric chains (type and chemical functions of the molecular monomers), their length, their entanglement, interactions, etc;
2. the degree of crystallinity Young modulus and elastic limit are growing functions of it;
3. the state of polymeric material: glassy, rubbery, viscous;
4. the temperature and the solicitation speed.

Interesting information can be recalled from Fig. 3.1: it shows a Young modulus to price-by-specific weight diagram in which are displayed the main families of plastics. Both are indicators to help choosing the right plastic for a particular application:

- Young modulus is a mechanical indicator;
- Price-by-specific weight is a design indicator: interest of the designer is to use as light and cheap material as possible. Moreover, beside the purchase price, heavy materials often lead to additional costs (lifting equipment, etc).

Ideal plastics for structural applications are on the left superior corner of Fig. 3.1, where at first both price and specific weight are low, so as to get the most light and economical structure, and secondly mechanical properties are high, so as to get the most efficient structure. Obviously, no material answers perfectly to these requirements. Two categories of plastics, which will be distinguished in 3.3, can be observed: the classical and most produced plastics, in blue, and the most resistant,

technological and expensive composites, in red, emphasized by two red arrows (glass or carbon fiber reinforced composites - FRP).
For our scope, particular interest will be held on mechanical and physical properties of plastics, in particular their elastic behaviour, which is determined by two principal quantities: the *Young Modulus* (E), the *elastic limit strength* (f_y,).

3.3 Classification of Plastics

The consequence of the great diversity of properties of plastics is the huge number of their potential applications (Departement, 2009). They are commonly classified according to their use or their behaviour.

3.3.1 On the behaviour

With reference to their behaviour, three categories exist:

1. Thermoplastics;
2. Thermoset plastics;
3. Elastomers.

Thermoplastics. Thermoplastics are composed of branched chains: they are reticulated. They have a melting point. As it is said (PlasticsEurope, 2015), these are plastics which soften on heating and then harden again on cooling.

For example, the Plastic Pipe and Fittings Association (PPFA) [5] states a thermoplastic as a plastic that can be repeatedly softened by heating and hardened by cooling and that in the softened state can be shaped by flow into a product by molding or extrusion.
Thermoplastics can support many of such cycles before enduring severe damages. Two different classes exist:

1. *Amorphous* Polymers: have no apparent order. At the micro-scale their structure is similar to a liquid or a glass. No melting temperature can be accurately measured, but they have a softening phase. They can provide transparency, good appearance, high dimensional accuracy and stability to the applications they are used for. On the contrary, they are highly sensitive to thermal or mechanical stress cycling or contact with chemical environments. They are characterized by low shrinkage and reep resistance. Examples: PS, PMMA, PC, PVC.
2. *Crystalline* Polymers: have an ordered structure in an amorphous matrix. The rate of crystallinity gives the importance of crystal structure throughout the material. This rate depends on the material and on the cooling during molding:

[5] `https://www.ppfahome.org/`

instantaneous or rapid cooling gives a low rate of crystallinity, whereas a long cooling would probably result into a very crystalline material. They have a good resistance to fatigue and chemical contacts, a smaller sensitivity to cracking and a low friction coefficient. Examples: PE (polyethylene), PET (polyethylene terephthalate), PTFE (polytetrafluoroethylene).

Thermoset plastics. Thermoset plastics have their macromolecules oriented in the three directions of the space. There is no melting point. The molding is obtained by using a crosslinking agent, a catalyst or hardener. In general, they are stiffer than thermoplastics and are more resistant to creep. Thermosets can be defined (PlasticsEurope, 2015) as plastics which never soften on heating once they have been molded. According to the PPFA they are plastic that, when cured by application of heat or by chemical means, changes into a substantially infusible product. The main families are: polyester, phenolic, epoxy, aminoplast, fibreglass reinforced plastics, PEX (cross-linked PE).
Elastomers. Known even as rubber, they are especially characterized by their exceptional deformability before failure. Their structure is reticulated and they are used above their softening temperature, or phase transition temperature. The most famous applications of elastomers are car tyres.

3.3.2 On the refinement

Another classification may be made according to the refinement of their process. Generally are distinguished between:

- the **Mass-Polymers**, such as: PVC, PMMA, Polyurethane, resins thermosets, polyolefins and styrene;

- the **Technical Polymers**, speciality polymers or composite materials, which possess better qualities. Among them: polyamides, PC, polyacetals, polyimides, polymer alloys and fiber reinforced polymers (FRP). Composite materials and especially FRP are a great font of innovation as their production volume and use are exponentially growing. However, they enter the category of high technology plastics, whose characteristics will not be detailed in this work. Further information can be found nowadays also in construction literature, such as for what concerns the Aberfeldy cable-stayed bridge (1992) (Skinner, 2009), (Burgoyne and Head, 1993), (Association, 2015), (Stratford, 2012).

3.4 Interest and use of plastics for construction

The main applications for plastics in industry concern packaging, construction, electrical, electronic applications and transport industry (Fig. 3.2).
In particular, for the domain of construction, second highest user of plastics after packaging in 2012 according to Plastics Europe (PlasticsEurope, 2015), plastics

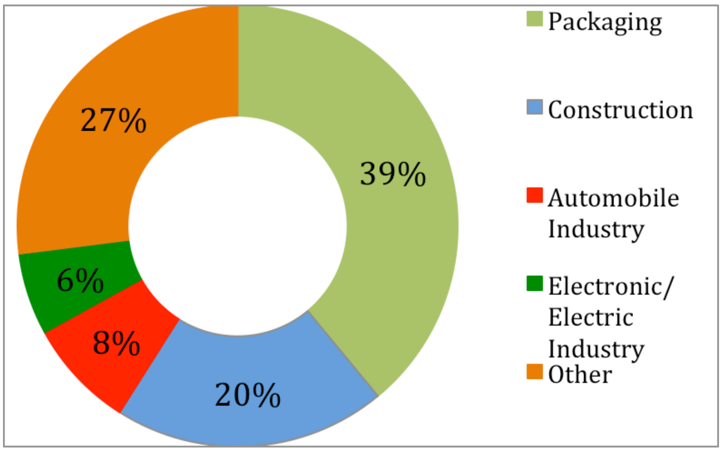


Figure 3.2: European total demand for plastics in 2012.

are widely used for their good strength to weight ratio, durability and corrosion resistance (do not rot, rust, need re-painting) and subsequent cost effectiveness, low maintenance, and great versatility. They are also easily formable, easily transportable and movable on site (Booth and Robb, 1968).
Nowadays, piping and conduit represents 35% of the plastic production for construction. Plastics are also used for cladding, skirting and thermal insulation. They constitutes profiles for windows and doors. They even furnish roofs. In this field, it is worth citing the Spanish initiative in Corbrera d'Erbre (Tarragona): Architect Ferran Vizoso has designed a PVC transparent light roof of 1050 m^2 area to rehabilitate the roof of an old church (Fig. 3.4).

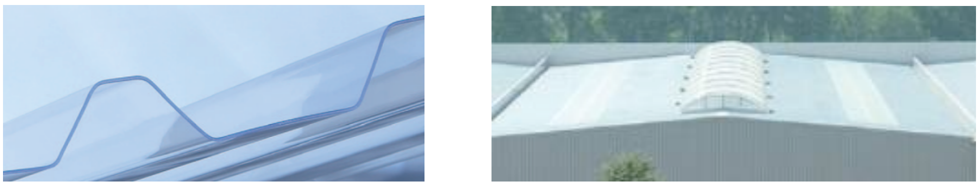


Figure 3.3: Flachdach Technologie, by the German company FDT.

These plastics are generally recyclable; in practice only a small part is recycled though. Another great field of innovation for plastics stands in its alloy with concrete, to optimize its qualities and decrease its environmental impact: superplasticizers to get ultra-high performances concrete, polyacrylates or polycarbonates to increase its mechanical strength reducing its weight or thermoplastic resins to make it 90% translucent.

3.4.1 Towards new prospectives

The rarefaction of fossil energies, the increase of the price of energy and the rising difficulties to manage wastes, strive ahead energy efficiency, waste management and recycling, taking into account the Life Cycle Analysis (LCA). Therefore, despite their fossil origin, plastics are in pole position to tackle such challenges as they are highly recyclable and efficient. Moreover, their nature makes them able to be designed to a very wide range of uses.

The most produced plastics are Polypropylene (PP), Polyethylene (PE) and Polychlorure Vinyl (PVC). Looking back to Tab. 3.1, PVC appears to be one of the most interesting plastics for our scope because it has among the highest mechanical properties of classical plastics and is though one of the most light and cheap of them. This provide it henceforth a worldwide use and supply. In particular, it is slightly better than PP and PE. Furthermore, a famous field of predilection of PVC concerns pipes and tubes. These advantages made the choice of PVC quite obvious for the sake of this study. More detail will now be given on its characteristics.

Figure 3.4: Roof of the church of Corbrera d'Erbre (Spain).

3.5 The PVC plastics

As it is said before, Polychlorure Vinyl (PVC) are a suitable choice towards a possibile structural purpose. Here more details will be given on its characteristics, bearing in mind that the object of this part is to introduce to PVC pipes design and the aspects relative to their plenned use.

Firstly, PVC belongs to the category of amorphous thermoplastics. It can also be considered a mass-polymers. Indeed, it is one of the most produced and widespread plastics. It is even the most used plastics in construction, as this sector absorbs 60% of PVC production [(6)]. The building sector is the first PVC consumer far ahead the packaging sector (Fig. 3.5).

PVC is one of the earliest plastics. It was discovered between the end of the XIXth Century and the beginning of the XXth Century, and used for the first time as pipe in 1933 in Germany. In North America, after the first intallation of a pipe in 1949, standards are introduced in 1960 by ASTM (Ch. 3.9). More than 30 millions tons are produced each year in the world. In America, it represents more than 70% of the linear footage of all plastics pipes and in 2004 the PVC water pipe market share even exceeded 78% (cf. PPFA).

(6) http://www.pvcconstruct.org

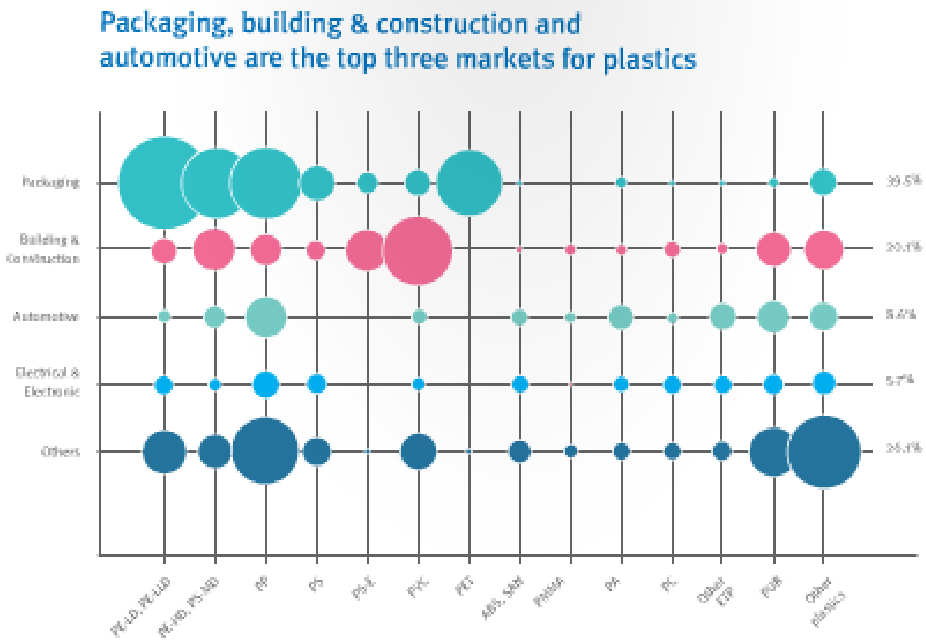


Figure 3.5: European plastic demand by segment and polymer in 2014 ((PlasticsEurope, 2015)).

3.6 PVC Structure

PVC is an *homopolymer* - which means it is produced from only one type of monomer - composed of barely ramified macromolecules chains. It is derived from marine salt (57% of its mass) and oil or gas (43%). In reality, PVC is made from chlorine - produced by an electrolysis decomposition of salt water - and ethylene, which is obtained from oil or gas via a 'cracking' process. Ethylene is though increasingly produced from sugar crops, corn or soybeans as a green alternative [(7)]. It is worth note that consequently and contrarily to most of other plastic, less than 50% of the weight of this plastic derive from fossil fonts (actually, it is the only one plastic material whose weight comes more than 50% from a mineral origin). For example, PE is 100% derived of oil or gas.

From the chemical point of view, PVC has a similar structure to PE, but, as its names presumes, it contains some chloride atoms randomly distributed along the chains. Such a polymer is called atactic, in contrast to isotactic polymers (typically crystalline polymers). The principal chains are prevented to align and PVC to crystallize because of sterically hindered chloride atoms (chloride is $_{17}$Cl, whereas Carbon is $_{6}$C: chloride atoms are much bigger than carbon atoms and thus obstruct the organic chains). That is why the molecular structure is amorphous, like glass. And it is indeed transparent. Colouration is only induced by the addition of plasticizers and fillers (Ch. 3.7).

[(7)] Plastics Europe: `http://www.plasticseurope.org/`

A polymeric chain contains 750 to 1500 Vinyl Chloride Monomer (VCM), whose formula is:

$$CH_2 = CH - Cl \tag{3.1}$$

3.7 Production processes

To improve safety and recycling, to allow recuperation of subproducts and to limit environmental impact, PVC production units nowadays implement closed cycles and automatic functioning. From raw natural material to finite PVC product, it comprises 6 steps (Fig. 3.6):

1. Salt and oil extraction;
2. Chloride and ethylene production;
3. Vinyl chloride monomer (VCM) synthesis;
4. Polymerization of VCM in raw PVC;
5. Blending of raw PVC with additives (stabilizers and/or plasticizers);
6. Transformation of PVC compound in finite products.

Figure 3.6: Scheme of PVC process.

Salt and oil extraction will not be detailed. Ethylene and chloride production are quickly covered in 3.6. VCMs are formed by basic direct chlorination or oxy-chlorination reactions. These monomers are gaseous under normal conditions, and therefore stored under pressure in order to keep them liquid. Further details will concentrate on elaboration of polymers and PVC materials. In the following parts, some conventions are set for the different forms that PVC takes throughout the synthesis:

- *Raw PVC or PVC resin* is the PVC polymer formed after polymerization, whose elements (cf. PPFA) are chemically bonded and cannot be disconnected by any exterior forces;
- *PVC compound* is the ready-to-use PVC transformed by additives;
- *PVC product* is a finite product. PVC has been moulded.

3.7.1 Polymerization

Here are presented the 3 different processes of manufacture of raw PVC. Raw material for all kinds of polymerization is constituted by VCM.
Suspension polymerisation. Suspension PVC is also known as S-PVC. PVC made from suspension is by far the most common.

1. During the first step of suspension polymerization, VCM is fed into the polymerisation reactor alongside water and suspending agents. The mixture endures high-speed agitation. Small VCM droplets are formed.

2. As a next step, an initiator or catalyst soluble in VCM is added in the pressurized and heated reactor (temperature ranges from 40°C to 60°C). In this conditions, the VCM droplets, suspended in water, become PVC slurry particles of $50 \sim 200\mu m$ diameter.

3. At the final stage of the S-PVC process, un-reacted VCM is separated from the suspension to be recycled and re-used. Water is removed, usually by centrifugation. The solid is dried to become a PVC non-toxic,odourless and inert white powder.

Emulsion and bulk polymerisation. These processes are alternative ways to product what we call raw PVC. However, these processes are far less common technologies. Emulsion polymerisation is mainly used for certain applications which require finer resin grades because it produces much smaller particles. This type of resin is either known as E-PVC (for Emulsion) or P-PVC, since it is often used as paste (especially for coating surfaces).
The product of bulk (or mass) polymerisation is similar resin to suspension polymerization, except that it is produced without water. Its main applications concern products that require good plasticising properties and high transparency.

3.7.2 Transformation of raw PVC into PVC compound

Raw PVC powder is mixed with additives to custom the specific properties required for diverse applications. Additives are the indispensable tool that parameters the properties of PVC material. They can make PVC extremely rigid as well as completely smooth. They also give PVC its colour. Not only they provide it protection against thermal degradation of polymeric chains during the successive processing phases, but they also limit their vulnerability to UV radii [(8)]. As a matter of fact, additives are the font of the great diversity of PVC types (Ch. 3.8).

The main additives are the following:

- *Stabilizers*: used to stabilize plastics under elevated temperatures, UV radii actions or chemical exposure and to limit aging;

[(8)]urlhttp://www.pvcconstruct.org/upload/documents/csiro-report-2001.pdf

- *Plasticizers*: PVC compound is naturally rigid. Plasticizers are used to soften and smooth it. Most used are phtalate-derivated such as DINP (di-iso-nonyl phtalate), DIDP (di-isodecyl phtalate), DEHP (di-ethylhexyl phtalate);
- *Pigments*: allow to give to PVC almost all possible colours. They are sometimes toxic;
- *Loads*: are used to reinforce fire resistance and modify some physical or electrical properties;
- *Lubricant*: are used to ease PVC transformation preventing it from adhering;
- *Fire delaying*: are added to counteract the addition of plasticizers, that are often inflammable (Ch. 3.13).

3.7.3 Transformation of PVC compound into finite products

The resulting PVC granules or powders are then moulded into the final product: tubes, membranes, etc (Ch. 3.15). Its description is the point of subsection 4.2.
The present section however will enunciate the different types, properties and behaviour of PVC compound.

3.8 Types of PVC

This section briefly introduces the different categories of PVC and then describes the different formulations used in the design of tubes and pipes.
The simplest difference can be made according to the input quantity of plasticizers. PVC mainly exist under two forms:

- "*smooth*" or "*soft*" PVC, technically named plasticized PVC, or **PVC-P**. They stands for around 30% of PVC production and are mainly used to create membranes or sleeves. Such plastics contains more than 20% plasticizers [(9)].
- "*hard*" or "*rigid*" PVC, called unplasticized PVC, or **PVC-U**. The PVC-U are used for any applications requiring a minimum rigidity, such as pipes: they indeed represents 40% of total PVC consumption (Augier, 2007). Generally, it is the most furnished type of PVC for industrial uses.

PVC-P (1.1-1.35 g/cm^3) is slightly lighter than PVC-U (1.3-1.45 g/cm^3), but it only has one third of the limit strength of plasticized PVC and far weaker elastic and isolating properties.
PVC-U can be itself declined in more specific versions such as:

(a) PVC-NI (Normal Impact): it is the most common PVC-U declination, it provides a normal resistance to impacts ($< 5k\,J/m^2$);

[(9)] urlhttps://solutions-in-plastics.info

(b) PVC-RI, PVC-HI (Raised Impact, Hight Impact): are different types of PVC with enhanced resistance to impacts (between $5\,kJ/m^2$ and $20\,kJ/m^2$ for PVC-RI), even at low temperatures (PVC-HI);

(c) PVC-T & PVC-TF: it is a special denomination for PVC used for doors;

(d) PVC-GLAS: for transparent applications;

(e) PVC-C: it is a post-chlorinated unplasticized PVC, which means that chloride content of PVC is higher. As a consequence it is more resistant (in particular to fire and corrosion) and has an excellent behaviour at elevated temperatures. It is consequently very used for pipes.

Many other denominations of PVC for pipes differ by their moulding and formatting, not by their chemical composition: f.e: **PVC-O**.
For simplicity, in the following, PVC-NI will be referred as PVC-U, to contrast the other denominations.

3.9 Reference Codes

Exploring comprehensively the content of the entire normative framework that concerns thermoplastics in general and PVC material in particular is not the scope of this work. Therefore, only some references of the American and international regulation systems (respectively ASTM [(10)] and ISO[(11)]) are listed.
These norms and specifications about PVC-U and PVC-C compounds can be found in annex, for building products or non pressure applications. ASTM and ISO also provide specifications for the testing and the determination of the properties of plastics.

3.10 Properties of PVC material

The main useful physical and mechanical properties of PVC as a material are compared (when appropriate) to the same properties of other classical construction material such as: wood, aluminium, concrete, steel, stone, bricks. For the sake of this comparison, distinction will be made between PVC-U, PVC-C and PVC-P.

3.10.1 American classification

To face the great variability of formulations and subsequent properties, regulation organizations have introduced standard designations for plastics, and in particular for PVC. For example, the ASTM (Ch. 3.9) classification (ASTM D1784), detailed in Tab. 3.3, involves 5 digits:

[(10)] The *American Society for Testing Material* edits more than 12,000 norms
[(11)] More than 19500 norms of the *International Organisation for Standardization* are active

1. Material - Base resin
2. Impact resistance [J/m of notch under notch]
3. Tensile strength [MPa]
4. Modulus of elasticity [MPa]
5. Heat deflection temperature under load (1.82 MPa) [°C]

		Cell Limits										
N°	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	[−]	PVC-U	PVC-C	VC[a]								
2	$[J/m]$	< 34.7	34.7	80.1	266.9	533.8	800.7	5				
3	MPa	< 34.5	34.5	41.4	48.3	55.2						
4	MPa	< 1930	1930	2206	2482	2758	3034					
5	$°C$	< 55.0	55	60	70	80	90	100	110	120	130	140

[a] Vinyl Copolymer.

Table 3.3: Class Requirement for PVC-U and PVC-C.

Most frequently used PVC for pipes is *PVC 12454*. Therefore, for PVC-U, the corresponding properties will be used in the following.

3.10.2 Physical properties

Given the nature of the application - formwork, pipes in exterior environment - the following physical properties have been considered (reference norm is indicated between parenthesis). Tab. 3.4 sums up information for the different types of PVC and main construction materials.

- *Density* ρ. It is expressed indifferently in g/cm^3 or t/m^3 (ISO 1183);
- *Water absorption* (DIN 53495). Secifically applied to polymers, it is defined as the amount of weight gain (%) experienced in a polymer after immersion in water for a specific duration under controlled environment [(12)];
- *Vicat softening temperature* T_{Vicat} (ISO 306). It may be expressed in K or °C, the determination of the softening point for materials that have no definite melting point, such as plastics [(13)];
- *Minimal temperature of use* T_{min}. Below this limit the material is fragile;
- *Maximal temperature of use* T_{max}. Beyond this limit there are non-negligible resistance and rigidity losses;

(12) `http://www.engineering-dictionary.org`
(13) `http://www.definitions.net`

- *Thermal dilatation coefficient* α_T. Expressed in K^{-1}, it measures the volume variation under temperature variation [(14)] (DIN 53752);

- *Thermal conductibility at 20° C*. Expressed in W/m/K, it measures the ability of a substance to conduct heat[(15)] (DIN 52612);

- *Oxygen index*. It is the minimal oxygen content that allows the material to burn. As a reference, oxygen content of air is 20%;

Properties	ρ [g/cm^3]	α_T [10^{-6} K^{-1}]	T_{Vicat} [°C]	T_{min} [°C]	T_{max} [°C]
PVC-P	1.3	150	[-][a]	-20	60
PVC-C	1.55	60 - 80	105	-40/-15	90/100
PVC-U	**1.4 - 1.5**	**70 - 80**	**75 - 80**	**-15**	**60**
Concrete	2.2 - 2.4	12	-	-	-
Bricks	1.8 - 2	5 - 8	-	-	-
Stone	1.5 - 2.9	5 - 13	-	-	-
Wood	0.4 - 1.2	4	-	-	-
Aluminium	2.6 - 2.8	23 - 24	-	-	-
Steel	7.85	10 - 20	-	-	-

[a] PVC-P is flexible so that it behaves like an elastomer, above its Vicat temperature.

Table 3.4: Physical properties of PVC and of different materials.

In the end, PVC is indeed among the lightest construction materials as discussed in section 3.2. Its main drawback is the sensitivity to temperature variations: its range of use is quite restricted by the fact that beyond 60°C, its use shall be avoided for smoothing. Even if the temperature does not overpass this limit, a reducing factor shall be applied on mechanical abilities. Morevoer, PVC-U is the most-dilating construction material.
However, the range [-15°C-60°C] covers all possible uses of PVC as a beam for usual applications in European countries.

3.10.3 Mechanical properties

Similarly, interesting mechanical properties, as showed on table 3.5, are the following. Data is given for a 20°C temperature:

- *Tensile stress at yield*σ_y. It is the stress at elastic limit under axial tensile force [MPa] (ISO 527);

(14) In reality, thermal dilatation coefficient depend on temperature, so that data is given for 20°C as an order of magnitude.
(15) It is determined by the rate of heat flow normally through an area in the substance divided by the area and by minus the component of the temperature gradient in the direction of flow ((Parker, 1984))

- *Strain level at yield* ϵ_y. It is the strain at elastic limit under axial tensile force [MPa] (ISO 527);
- *Young modulus* E. It is the slope of an elastic stress-strain diagram [GPa] (ISO 527);
- *Poisson modulus* ν. One measures transversal deformations [-];

Properties	$\sigma_y{}^a$ [MPa]	ϵ_y %	E [GPa]	ν [-]
PVC-P	26	-	-	-
PVC-C	55 - 70	3 - 4	2.3 - 3.4	
PVC-U	**36 - 55**	**1 - 4**	**2.2 - 3**	**0.4**
Concrete[b]	-20/-80	0.2 - 0.3	30 - 40	
Bricks	2-8 & 15-60[c]	1-8 & 3-13		
Stone	0.5-30 & 5-220[d]		20 - 25	
Wood	10 - 11	-	1 & 7-10	
Aluminium	80 - 160	0.1 - 1	72	
Steel	200 - 500	2	190 - 210	0.4

[a] Default values are tensile. Compressive strengths are indicated with negative values.
[b] Concrete from C20 to C80 are considered.
[c−d] Different strengths exist because the material is not isotropic and homogeneous .

Table 3.5: Mechanical properties of different construction materials.

PVC is indeed *one of the most elastic and deformable materials* because of its low Young modulus. However, it makes its sensitivity to temperature easy to handle: a restraint would generate less efforts in PVC than in steel. For example, if σ_{pvc} and σ_{steel} are the stress induced by such a restraint under an increase of temperature ΔT:

$$\frac{\sigma_{pvc}}{\sigma_{steel}} = \frac{E_{pvc}}{E_{steel}} \cdot \frac{\alpha_{T,pvc}}{\alpha_{T,steel}} \approx \frac{2}{200} \cdot \frac{80}{20} \approx 4\%$$

Tensile and compressive strengths reach 50 MPa, which is decent and even more than wood. Note that PVC can handle both compressive and tensile stresses.
In accordance to ASTM classification for PVC 12454, the following properties on Tab. 3.6 are considered as common minimum properties for a classical structural PVC.

Properties	σ_y [MPa]	ϵ_y %	E [GPa]	ν [-]
PVC-U	48.3	1.75	2.76	0.4

Table 3.6: PVC mechanical properties for the present work.

*From now on, this document will exclusively deal with unplasticized PVC (**PVC-U**) and its derivatives, because it is the type of PVC that is used for tubes and piping* *systems.*

3.11 Structural Behaviour

Plastics do not behave under loading as metals: they are not elastic: like concrete, they have a visco-elastic behaviour (Ch. 3.2). This means a plastic material will behave as if it were a combination of elastic solids and viscous fluids. Therefore, their real stress-strain relationship is non-linear. Two main consequences emerge from this property: strain is not proportional to stress and strain is not independent of loading time. Actually, for viscous-elastic materials, total strain $\epsilon(t)$ can be written as:

$$\begin{aligned} \epsilon(t) &= \epsilon_\sigma(t) + \epsilon_{sh}(t) \\ \epsilon_\sigma(t) &= \epsilon_e + \epsilon_v(t) \end{aligned} \tag{3.2}$$

Where:

- $\epsilon_\sigma(t)$ is the mechanical strain, depending on solicitation and time;
- $\epsilon_{sh}(t)$ is the strain due to shrinkage (Ch. 3.11.2);
- ϵ_e is the classical elastic instantaneous strain;
- $\epsilon_v(t)$ is the - time dependent - viscous strain: ϵ_v is the object of present section.

At short-term, exerting a force F on a plastic sample will induce instantaneous deformations and stress: this is the elastic behaviour. In long-term though, maintaining this force F on the same sample will lead to delayed additional deformations. These deformations can reach up to 3 times the instantaneous deformations. When removing the force, delayed deformations are not cancelled: the are residual. Such a behaviour is a viscous behaviour. This phenomenon is called creep.
On the contrary, imposing a deformation ϵ to the same sample will induce at short term an instantaneous reaction force F. Maintaining the same deformation will though engender a decrease of the reaction F. This phenomenon is the dual phenomenon of creep: it is called relaxation.
However, as stated in the Unibell's guide for "Thermoplastic Pressure Pipe Design and Selection" (UNI-TR-7-01, (bell PVC Pipe Association *et al.*, 2002)), even though plastics do not behave elastically, most of the design equations that have been derived on the *assumption of elastic behaviour can still be used, provided the strength values are appropriately established.* The use of elastic equations requires the selection of strength values that account for long-term loading response.

3.11.1 Design quantities

Tensile limit stresses at yield or at failure are stresses determined by a test under specific conditions: the test duration is very limited (a few minutes) and the solicitation is particular (most frequently tri-axial). The corresponding procedure

is regulated by an ISO norm. Therefore, both indicate an order of magnitude of the tensile abilities of a material and allow its comparison and ranking with other materials.
But these two limit stresses do not give any information on effective (or on-site) mechanical limits of the material: PVC is indeed a visco-elastic material, which means its mechanical answer will depend on the duration and the nature of the solicitation (frequent, continuous, etc). A PVC pipe is actually used during many years: in comparison, the result of a tensile test is instantaneous. As a consequence, the resisting strengths of a thermoplastic material such as PVC need to take it into account.
Moreover, a realistic approach would have to consider the phenomenon of fatigue: repeated cyclic stressing can cause failure, as for any construction material, even for solicitations far inferior to the elastic limits.
Thus, to cope with this requirement, three distinct strengths have been defined:

(a) Long-term Strength;

(b) Short-term Strength;

(c) Cyclic Strength.

According to the project situations, three different design checks have to be done.
Usually and as stated in Unibell's[16] *PVC Main Force Design* guide, each SDR is associated to different admissible internal pressures, depending on the type of solicitation: pressure Ratio (PR) is associated to long-term situations and Short-Term Ratio (STR) is linked to short-term designs.
Young modulus is also affected by visco-elasticity: they have different values, according to long-term or short-term design. As for concrete, short-term moduli E_{ST} are often three times as high as long-term moduli E_{LT}:

$$E_{ST} \sim 3\, E_{LT}$$

Orders of magnitude are given in Tab. 3.7 for PVC and other materials.
These long-term and short-term values will be alternatively used in design for long-term or short-term situations.
Procedures and values for hydraulic pipes such as found in (ASTM, 2004), (Spangler and Shafer, 1938) and (ASTM, 2009) are the only example of structural design of PVC. It takes into account visco-elasticity and allows to use equations of elasticity as for concrete.

3.11.2 Time-varying volume variation

Time varying volume variations are not intended the volume variations linked to temperature. These are taken into account thanks to the thermal dilatation coefficient (defined in Ch. 3.10) which links volume and temperature variations.

[16] Unibell is an American association of plastic pipe manufacturers.

Material [MPa]	$\mathbf{E}_{LT}$ [GPa]	$\mathbf{E}_{ST}$
PVC	984	2.8
ABS	457	2.1
PE	155	0.77
Concrete C30/35	-	-
Steel	200	200
Aluminium	70	70
Ductile Iron	168	168

Table 3.7: Long-term and Short-term design value for PVC and other materials.

As seen in section 3.11, time-varying volume variation is called *shrinkage.* It is mainly known of civil engineers because it affects concrete. This paragraph recalls its principal characteristics for concrete before describing the shrinkage of plastics.

Shrinkage is a contraction of plastic after moulding. As for concrete, it is in general undesirable in PVC products, as it affects dimensional stability: it can f.e generate oil canning, or permanent warpage of profiles if it is greater in the edges than in the center.
PVC is subject to shrinkage when moulded, cooled and solidified. It would result from re-arranging molecules at micro-scale during moulding. Therefore, in comparison of the lifetime of PVC product, *shrinkage is instantaneous* and we can write the expression as:

$$\epsilon_{sh}(t) = \epsilon_{sh} \tag{3.3}$$

Further information on the transformation of PVC into finite products is given in section 4.2.

Generally speaking, There are two types of shrinkage:

- Volumetric shrinkage: it affects the entire volume of a moulded piece;
- Linear shrinkage: it associates the effects of the flow to the effects of the contraction. Molecules are mostly oriented in the direction of the flow, therefore longitudinal shrinkage is always higher than transversal shrinkage.

As explained above, a measurement of shrinkage should account for a volumetric change. Therefore, an indicator will be a ratio, called moulding shrinkage factor(ϵ_{sh}), between the dimensional difference mould-plastic and the mould dimensions, its value about 0.2% to 2%:

$$\epsilon_{sh} = \frac{L_0 - L}{L_0} \tag{3.4}$$

or

$$\epsilon_{sh} = \frac{V_0 - V}{V_0} \tag{3.5}$$

where:

- L_0 and V_0 stand for the cavity dimensions or volume;

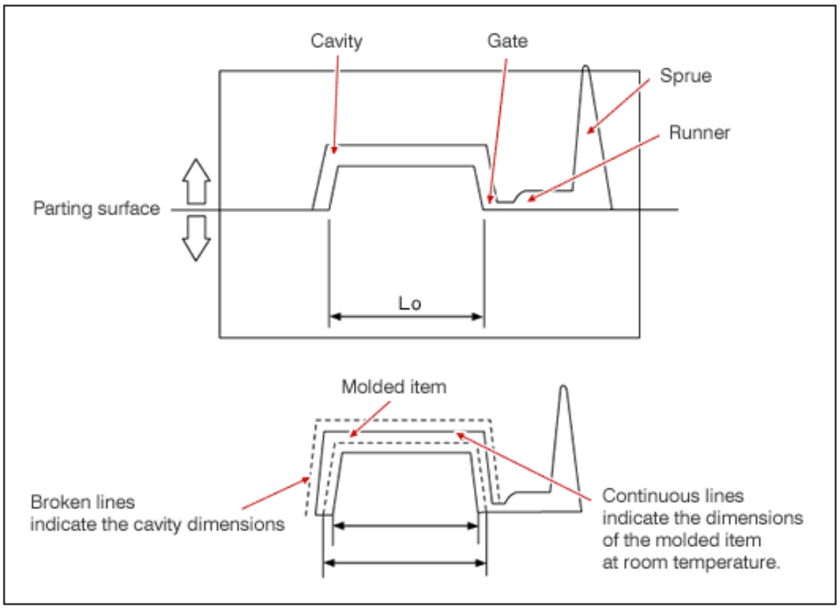


Figure 3.7: Two parts of the mould and cavity (at the top) and finite contracted product (at the bottom).

- L and V stands for the dimensions or volume of the moulded product at room temperature (usually 20°C).

The shrinkage of a moulded part can be affected by many factors. Here are described the main ones and their effects on shrinkage: '+' (resp. '–') means an increase of the factor is favourable: it decreases shrinkage (resp. unfavourable):

+ injection speed/rate and pressure;

– wall thickness;

– temperature;

± nature and quantity of the filler;

+ cooling duration;

+ size of the nozzle and of the gate;

+ venting of the cavity;

– rate of crystallinity.

If shrinkage ratio is sufficiently well-known, the molded item can be given the intented dimensions by enlarging its dimensions V by the amount of shrinkage ϵ_{sh} to get the volume of the mould V_0:

$$V_0 = \frac{V}{1-\epsilon_{sh}} \simeq V\,(1+\epsilon_{sh}) \qquad \epsilon_{sh} \ll 1 \tag{3.6}$$

An order of magnitude of shrinkage is given in Tab. 3.8 [17]. PVC-U is anyway one of least shrinking plastics.

Material	Shrinkage[%]
PVC-U	0.2 - 0.4
PP	0.2 - 0.8
ABS	0.4 - 0.7
PVC-sm*	0.5 - 2.5
PVC-P	1 - 3
PE	1.5 - 3.5

* PVC semi-rigid.

Table 3.8: Shrinkage ratios for different plastics.

Contrarily to concrete shrinkage, shrinkage of plastics does not affect the long-term statics: it is due to its transformation and can be ignore if the PVC products do not have visible defaults. The pipes that will be considered in section 4.1 are without default, as they come from retails. Therefore, shrinkage is not taken into account in further conduct of this work.

3.11.3 Durability of PVC

Many aspects make PVC a durable material. It is indeed:

1. Rot-proof: in contrast to organic material such as wood;

2. Not sensitive to aging: no alteration of properties after years. Experience and supporting evidences teaches that the buried tubes and pipes keep their technical characteristics after more than 50 years of use. No alteration could be observed when unearthed. Durability concerns also appearance as no colour or shape alteration occur when aging;

3. UV-radii: thanks to its additives, PVC is protected against UV deterioration. However, the long-term effects of UV radii on PVC structure and their effective effects on physical and mechanical properties are not clearly established. Some literature warns about long periods of direct exposure to sunlight, that would discolor the pipe surface and slightly reduce its impact resistance, sometimes making necessary to cover it with a opaque substance;

4. No sensitive wear;

5. Recyclable: even after decades, PVC can be 100% recycled;

[17] `www.pitfallsinmolding.com`, `www.stelray.com`

6. Chemical resistance: additives provide PVC protection against chemical attacks of a normal environment;
7. Waterproof: PVC is by nature 100% waterproof;
8. Weather resistant: this ability comes from both its waterproofing and its chemical resistance;
9. Rust-proof: PVC does not rust and therefore it does not require any cover (like painting for steel);
10. Ductility: does not crack, even under shock and frost. Brittleness only appears for temperatures below the minimal temperature for use (cf. 3.10).

As its use is quite recent, real time-lasting will only be known in decades. PVC used for building applications (f.e windows) are replaced and recycled in most cases after the renovation of the building, and not for wear or malfunction reasons.
The phenomenon of fatigue, very important for what concerns durability, will be detailed in the following. It is important to notice that fatigue sensitivity can vary for the same plastic depending on molecular structure, formulation and fabrication quality.
For all those reasons, PVC is often the preferred choice for many different long-life and outdoor applications. In fact, medium and long-term applications account for some 85% of PVC production in the building and construction sector(18). For example, it is estimated that more than 75 % of PVC pipes will have a lifetime in excess of 40 years with potential in-service lives of up to 100 years. In other applications such as window profiles and cable insulation, studies indicate that over 60% of them will also have working lives of over 40 years.

As such, durability is one the hugest advantages of PVC as material for civil engineering because whatever project lifetime, it does not not need any particular maintenance.

3.12 Possible connection with other materials

PVC is also often associated with ABS (Acrilonitrile-Butadiene-Styrene), another polymer, to realize plastic semi-finite products, like pipes. Indeed, plastic pipes can also associated with other tyep of material, such as steel. Particular examples are given for the case of pipes in paragraph 4.3.6.

PVC is planned to be used to form concrete. Existing plastic formworks do not have significant structural role, thus association and compatibility between plastic and concrete have not been studied. No detail nor scientific work substantiate the important hypothesis of compatibility between concrete and PVC under loading

(18) `www.pvcconstruct.org`

conditions. Adding lubricant to PVC compound (Ch. 3.7) smooths PVC, but its effect on compatibility can not be evaluated.

3.13 Project parameters and characteristics of use

It is worth reporting here an important phenomenon when dealing with civil engineering structures and materials: fires. Even though the behaviour under fire affects first and foremost residential and industrial buildings components, a study of PVC characteristics would not be comprehensive without noticing the main following features.

Fire Behaviour. PVC products are difficult to ignite. As a matter of fact, heat production is comparatively low and they tend to char rather than generate flaming droplets.

Fire Resistance. Even if PVC is naturally fire delaying, and resist even better to fire than other plastics, PVC products burn in presence of a flame. Though, they are self-extinguishing, which means that it stops burning if the ignition source is withdrawn.

Emissions. If there is a bigger fire, for example in a building, PVC products will burn and emit toxic substances like all other organic products. The most important of them is carbon monoxide (CO), which is responsible for 90 to 95 % of deaths from fires. CO is one of the most dangerous gas, since we cannot smell it and most people die in fires while sleeping. Moreover, as its chemical formulation shows, CO is emitted by all organic materials (wood, textile or plastics).

Finally, as some other materials, PVC also emits acids, whose emissions are irritating if breathed. In particular, when burning PVC emits hydrochloric acid (HCL).

3.14 Situation of the market

The price of plastics is largely depending on the class of plastic (1-2 €/kg for PP - PVC and more than 50-100 €/kg for more technological plastics).

For PVC, different data are available. The following comes from values of the French finance department and the French customs(19). The prices are a good indicator for international rates. Three different products are distinguished:

- Poly [vinyl chloride], in primary forms, not mixed with other substances: it relates to raw PVC, as defined in section 3.7 (ID: 39401000).
- Poly [vinyl chloride] in primary forms, plasticized, mixed with other substances (PVC-P) (ID: 39402200);
- Poly [vinyl chloride] in primary forms, non-plasticized, mixed with other substances (PVC-U) (ID: 39402100).

(19) lekiosque.finances.gouv.fr

These will be compared to aluminium (ID: 76012020, aluminium alloys, unwrought, in slabs or billets) and steel (ID: 72241090, alloy steel other than stainless steel, ingots or other primary forms, excluding tool steel and other than ingots and products obtained by continuous casting).
Two numbers are available:

(a) *CIF values*: imports are recorded on the basis of invoices CIF (Cost, Insurance, Freight). It includes the price of the product itself, transportation costs and insurance required for its routing on the territory.

(b) *FOB values*: exports are identified on the basis of invoices FAB (Free On Board): including the cost of transport to customs clearance, excluding of those incurred outside the territory to bring the goods to the consignee.

Both numbers do not show only the real value of the good, as both include additional costs. As a matter of fact, Tab. 3.9 sums up the average FOB & CIF values ofraw PVC, PVC-U and PVC-P in 2015 from France to the rest of the world.

PVC Type	**FOB Values**			**CIF Values**		
	Volume [t]	Total value [k€]	Average price [€/t]	Volume [t]	Total value [k€]	Average price [€/t]
Raw PVC	726,919	603,062	829.61	230,930	200,978	870.30
PVC-U	35,834	48,186	1344.70	47,123	51,523	1093.37
PVC-P	39,813	88,556	2224.30	30,359	41,366	1365.86
Alum.	95,503	245,580	2571.44	251,307	544,373	2307.44
Steel	77,772	175,750	2259.81	8,011	38,623	2463.19

Table 3.9: Import and Export prices for PVC compounds.

These values, even if very approximative because relative to special categories of uses and to one country in particular, clearly show that steel and aluminium as raw materials are twice as expensive as PVC-U compound. Therefore PVC is definitively interesting from the economical point of view. Paragraph 4.7 shows similar comparison for semi-finite products such as pipes.

3.15 Main applications

Some applications of PVC in various fields will be shortly proposed whatever the type described be. A particular application will be more extensively discussed in section 4.1.
As shown in Fig. 3.5, principal applications (60% of total world PVC consumption) relate to construction. This ratio rises to 3/4 in North America[(20)].

[(20)]Source: PPFA - Plastics Pipe and Fittings Association

Applications in construction. Main applications in construction regard buildings. As said before, this due to PVC's resistance, lightweight, durability and versatility qualities. Especially, it is worth citing:

- window and door profiles;
- joineries (imitation of wood appearance);
- internal and external cladding;
- pipes and fittings;
- wallcovering and flooring.

(a) As roof for a tollgate (`www.pvcdesign.org`).

(b) As printing support for advertisement.

Figure 3.8: Example of use of a PVC membrane.

In public works, PVC is mainly used for *various piping systems* (Ch. 4.1) because of its lightweight and resisting strength. Especially, for rainwater, soil and waste systems because of its inertia, chemical resistance and waterproofing, as well as for roofing membranes (Fig. 3.8a) because of its versatility. The latter is nowadays at stake because of the recent developments in matter of complex shapes, funicular structures and suspended membranes. As an example, the 50,000m^2 of the roof of the Stade de France stadium, a 80,000-seat stadium built to welcome footbal World Cup in 1998.

Other applications. Thanks to PVC's excellent flame retardant and electrical insulation properties, other uses of PVC include above all *wiring and cable* ducting for power, data and Telecom networks and advertising supports (Fig. 3.8b).

It is also used in cars, since in Western Europe, cars currently produced contain from 10kg to 16kg of PVC.

As a conclusion, PVC has been extensively used in a wide range of construction products for over half a century. However, PVC applications do not require any particular mechanical resistance except supporting PVC's self-weight. They are neither calculated nor dimensioned to withstand particular load or forces. Exception are pipes: in piping systems, PVC plays a real and prominent structural role: beside bearing self-weight, *it supports the weight of the transported fluid, eventual dynamic effects, local reactions and internal pressure.* That is the reason why the main normative literature regards piping systems dimensioning.

3.16 Concluding remarks

PVC is light, it has a broad and flexible range of utilization. It is quite weak as a construction material, but it ensures no brittleness, as it offers flexibility and ductility. That is why *PVC pipes have 1/6 of the weight of most non-plastic pipes* according to PPFA.

PVC pipes are is perfectly adapted to contain concrete: this plastic is an excellent insulator, it is inert, so that it provides a good protection against chemical and environmental actions, including additives and cements of concrete and it is waterproof, to avoid concrete leaks.

Other advantages are its *availability*: over 100 PVC piping products plant is North America, and *recyclability*, as almost 100% of PVC can be recycled.

Describing PVC as a raw material is not sufficient to introduce it as a decent construction material. One shall examine the finite product which is planned to be used. Thus, discussion move on on further technical details on PVC pipes.

Chapter 4

Products made by PVC

Semi finished products are the resultant of the last production process of PVC: transformation (as it can be said in the previous Chapter). It allows to shape in particular form of pipes or fittings to PVC compound: engineering structural design will be introduced considering a pipe as a particular type of beam.

4.1 Semi-finished products

The first plastics pipes were made in the 1930's. During a few decades, they were then used to replace corroded metal pipes. Their first applications therefore concerned drinking water supply. From that time plastic pipes have been implemented for their lightweight and flexibility qualities with respect to steel pipes(1). Buried pipes are commonly classified as "rigid" or "flexible". These denominations arise from the notion of rigidity of the system backfill-pipe. It corresponds to the ratio between the rigidities of both pipes and backfill. Therefore, it accounts for relative deformability of the pipe with respect to the backfill. For example, a "rigid" concrete pipe will deform less than adjacent backwill while a "flexible" PVC-U pipe will have opposite behaviour. It is more or less at that time that PVC started to be produced industrially.
As said in section 3.5, the chemical resistance to ordinary chemicals such as acids, bases, salts, and oxidants combined to its mechanical properties has quickly enhanced the use of PVC pipes in the field of sewers, soil and waste, for pressure and non-pressure tubes.
Their use continued to widen as PVC pipes turned out to be cost-effective, long-lasting, easy to install and low maintenance requiring.

4.2 PVC Transformation techniques

There are many different ways to transform PVC compound into PVC products:

- *calendering*;

(1) `www.teppfa.eu`

- *extrusion*;
- *blow-moulding*;
- *injection moulding*;
- *expansion*;
- *thermoforming*;
- *coating*;
- *rotational moulding.*

They will be shortly described, particular mention will be made of the most useful techniques to shape pipes and fittings. For any transformation, the moulding process can induce a significant level of residual stress, as mentioned with shrinkage in section 3.11.2.

Calendering. This technique is derived from the rubber and paper industry production techniques. Calendering was the first processing procedure for plastics. It has become widely used especially for PVC processing into films and sheets of varying width and thickness, with wide range of surface finishes.

The main applications are:

- sheets and plates for thermoforming packaging or shaped components;
- rigid plastic sheets for the papermaking or printing industry (f.e credit cards);
- clothing and decorative details (wall coverings, curtains).

After blending of additives and heating in special machines, as PVC is an homogeneous mass, it is entered in the calender. The calender is constituted of 4-5 parallel cylinders whose spacing is progressively decreasing. At the exit, the semi-finished passes the winding machine (if film) or the cut (if sheet), as shown on Fig. 4.1.

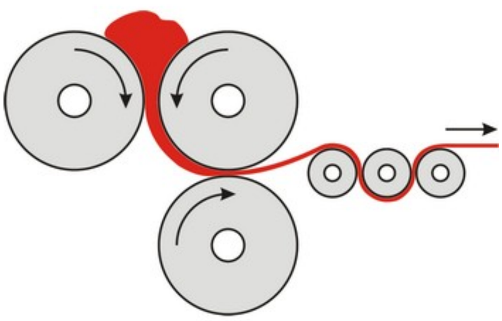


Figure 4.1: Calendering process: PVC compound passes between cylinders.

Extrusion. It is currently the most widespread transformation process for plastics material in general. Its main application is the production of linear manufactures such as pipes and profiles (window frames) because they can be made to any length. Another advantage lies in the possibility to integrate a coupler for rubber seal (Ch. 4.3) It is also used to derive thin films, continuous coatings or cables and wires.

The main body of the extruder is a cylinder within which rotates a or more worm screws. PVC compound is fed directly by a hopper into a cylindrical barrel, where it is progressively heated until melting. The rotational movement of the screw homogenizes and, by extreme pressure, transports it towards the outlet hole. This matrix, called die, is shaped according to the desired type of profile. It can thus be a flat section (for the production of films or laminates), a circular section (for the production of tubes or tubular films) or a more sophisticated section (for the production of profiles). Once forced into the die, the product is cooled so that it maintain permanently its dimensions. Procedure is shown on Fig. 4.2.

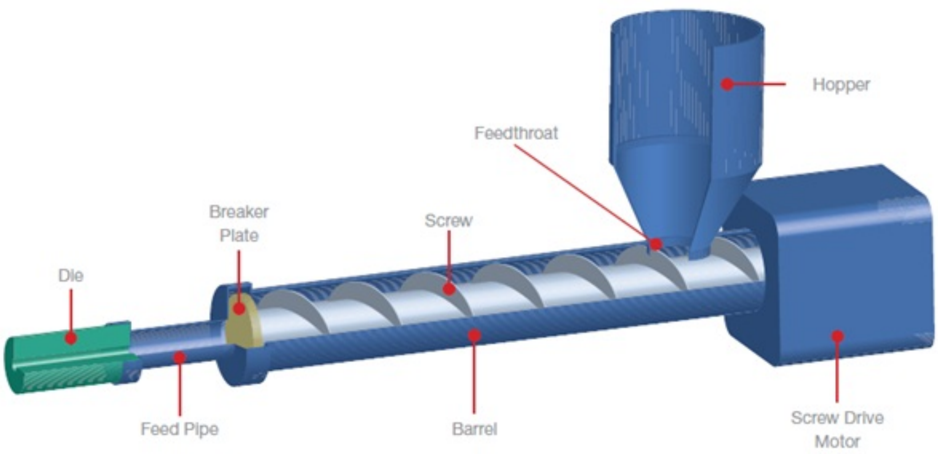


Figure 4.2: Extrusion process: PVC compound passes from the hopper to the die.

Injection moulding. It allows the production of very complex and important objects (from the body of typewriters and computers to artificial transplant prostheses) with great precision of details. Most voluminous pipes are injection moulded, as well as all standard and most non-standard PVC fittings. Based on the type of the press, there are two different processes. Plastic material is placed in a heated cylinder, where it is melt. Then it is pushed toward a small nozzle by a piston or a screw. Hence it is injected at pressure into a mold cavity to completely fill the transition. Once cooled and solid, the object is extracted from the mold.

Blow-moulding. This technique allows for the production of hollow objects: bottles can hence be given an infinite range of sizes, shapes and colors. The technique of blowing is mainly combined with the extrusion process (extrusion-blow moulding process) or - less frequently - with the injection process (injection-blow-moulding process). The only difference stands in the type of material introduced in the mold: in the first process, they are already extruded sections which are cut the correct dimension, whereas in the second process, hot plastic compound is directly injected. Then, for both processes, air is blown so as to inflate and make plastic perfectly adherent to the walls of the mold itself. The mold actually constitutes the negative impression of the object. After a short cooling, the mold is opened, the artifact is extracted and the cycle begins again (Fig. 4.3).

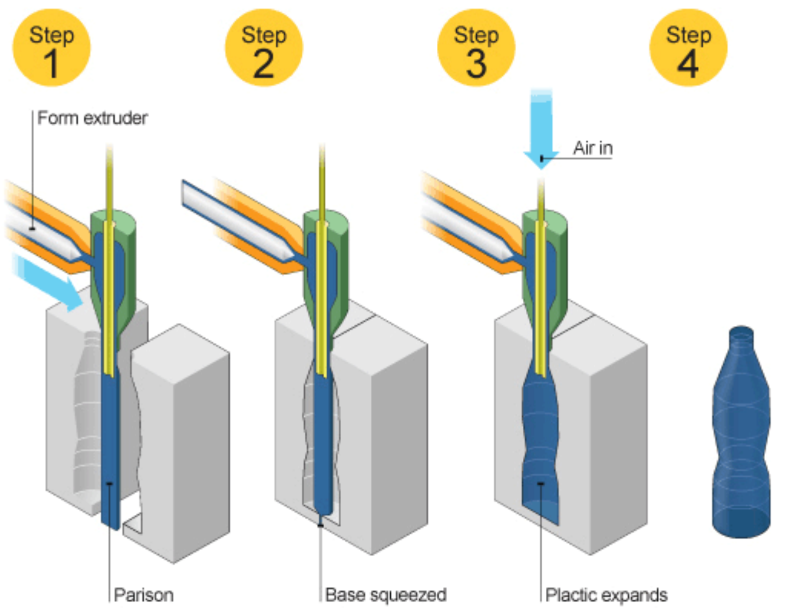


Figure 4.3: Blow-moulding process: particular shape is given by the mold.

Expansion. The term expansion refers to a machining technique in which the specific weight of the starting polymer can be adapted to obtain lighter materials with a cellular structure. Those plastics are used in thermal and acoustic insulation applications, in imitation leathers or in lightened structures such as tubes and profiles. PVC foams can be rigid, semi rigid, flexible, depending on the formulation and the degree of expansion used. The cell structure can be obtained by various processes, all including gas.

The combination of *extrusion* and *expansion* techniques allows the production of **PVC-O**, also known as Bi-Oriented PVC. The process, developed in the early 1970s, lies on the polymeric properties of PVC and on their three-dimensional molecular orientation. As said in section 3.6, every plastic is constituted of long disorganized molecular chains. Indeed, PVC stands among the amorphous polymers. A wise design would take advantage of the preferential dimension to make it carry the load: doing so, stress is supported by covalent molecular bonds (in the direction of the chains) which are strong interactions, instead of indifferently by covalent bonds and reticulation bonds and other weak interactions between chains.

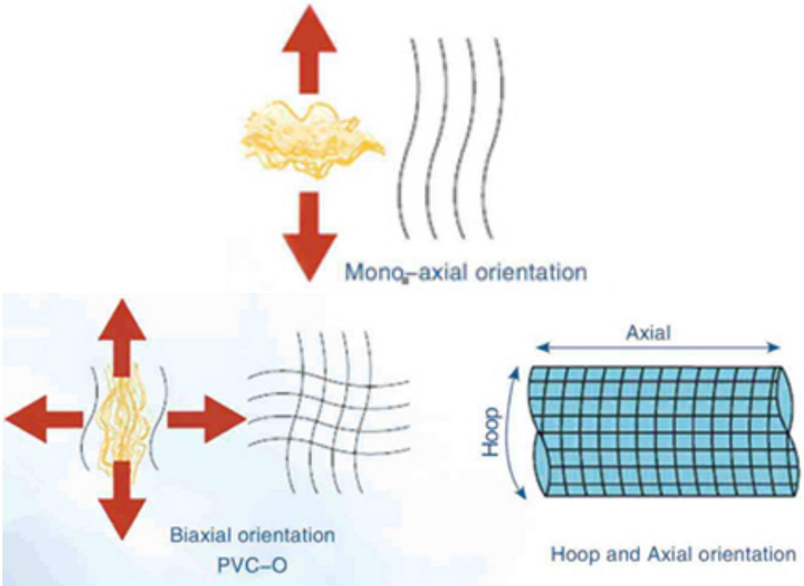


Figure 4.4: Mono-axially and bi-axially oriented PVC.

This principle is similarly used when dealing with composites materials and especially Fibre Reinforced Material (FRP), for which fibres with very high tensile strength are woven in one or two preferential direction(s) and set in a matrix or a resin. Whereas after extrusion, classical PVC-U is mono-axially oriented, for PVC-BO, molecular orientation is achieved in two successive phases:

1. PVC pipe is *extruded* at about half the diameter and twice the thickness of the finished **PVC-O** pipe. This unexpanded pipe, called starting stock, is longitudinally stretched;

2. Then, the starting stock pipe is *expansed*, being pulled over a mandrel: the diameter of the pipe is doubled. This stretches the pipe in the radial direction, reorienting the molecules to become biaxially oriented, as shown on Fig. 4.4.

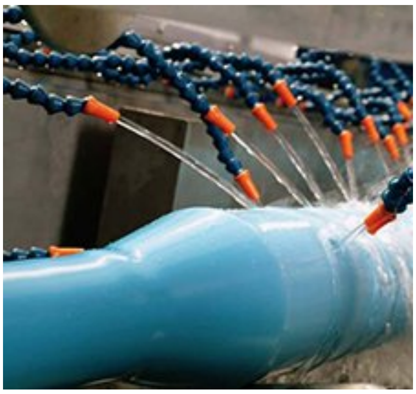


Figure 4.5: Once expanded in radial direction, PVC-BO is cooled.

This new material [2] has twice the tensile strength and three times the impact resistance of classical PVC-U (AUTHORITY, 2013)-(Association, 2002) and keeps its corrosion and chemical resisting qualities. As a matter of fact, for the same applications, equivalent PVC-O pipes are thinner[3] and lighter. They also have larger internal diameters (this finds a huge interest when dealing with project parameters as it allows to lower flow velocities and reduce pumping costs). Finally, this gives PVC-O pipes *more flexibility* and thus provide about *three times the resistance of PVC-U pipe to cyclic fatigue.*

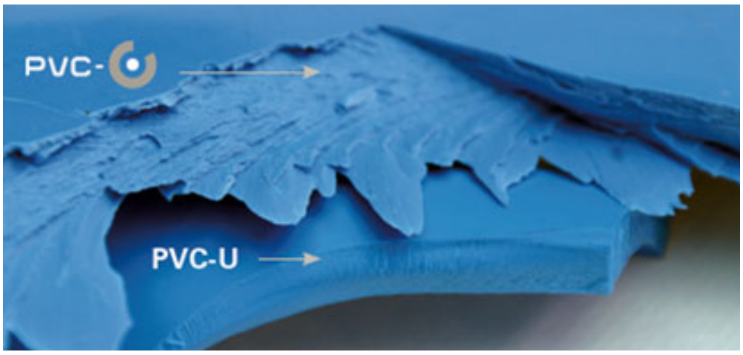


Figure 4.6: Circumferential direction is preferred for PVC-BO (`interempresas.net`).

Thermoforming. By effect of pressure, thermoforming allows to model rigid thermoplastic films, without reaching melting temperature, realizing cavities. In the thermoforming under vacuum process, a material sheet is fixed to a support above the mold and heated. The air is then sucked from the space separating the plastic sheet from the mold, by creating a depression: the plastic sheet is pushed against the mold by the atmospheric pressure above, and assume its shape. In the contrary, in the thermoforming under pressure process, heated plastic sheet is made adherent to the mold by the pressure exerted by compressed air.
Coating. There are two techniques to coat the surfaces of materials with plastics:

- Dip-coating, immersion in a fluid bed or plastisol;

- Coating by covering.

Immersion is mainly used to coat metal objects. A plastic material powder is suspended in a flow of hot air in a closed environment. The object to be coated is pre-heated so as the powder to adhere to its surface, forming a layer of the desired thickness. It is finally placed in a baking oven where the heat melt the powder and turns the coating into a continuous layer.

[2] PVC-O is not chemically speaking a "new material" because its chemical composition remains unchanged. Although, its physical microstructure has been modified: in this sense we deal with a new material.
[3] According to `www.thinkpipesthinkpvc.com.au`, the reduction of wall thickness would reach between 40% and 60% compared to other materials.

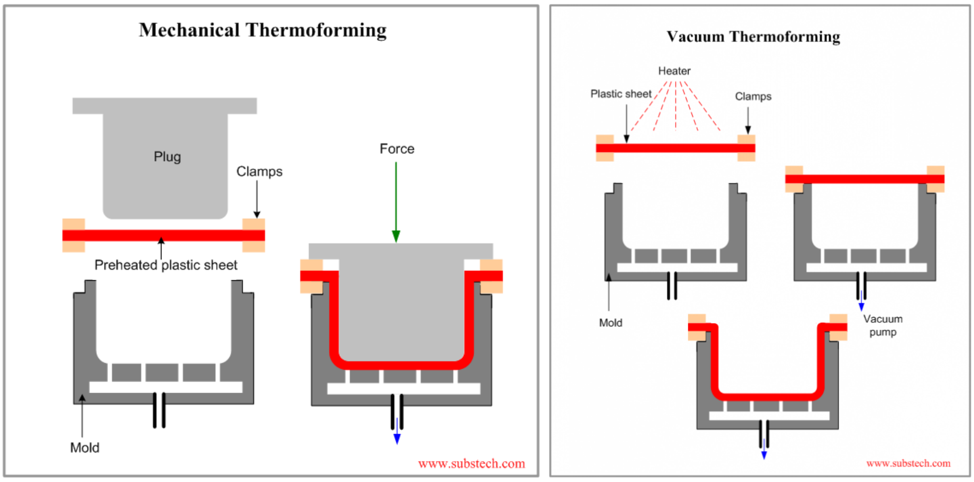


Figure 4.7: Vacuum and pressure thermoforming processes (`www.substech.com`).

Rotational moulding. Rotational moulding is applicable to powder (dry blends) or paste (plastisol) PVC compounds. Adherence to the mold is obtained by a centrifugal force. Application can be found in the automotive industry (car dashboards) or in the game industry (dolls, balls). Closer to our purposes, it is sed to produce large inspection chambers, water and septic tanks, although from polyethylene (PE) or polypropylene (PP).
In the next development, by *piping systems* are intended the associative systems constituted by the pipes and appropriate coupling tools, or fittings.

4.3 Connections

The objective of this part is not to make a comprehensive presentation of the catalogue of PVC tools. It will confine to explain the functioning of a PVC piping system and to detail the main useful connections. Plastic pipes association is very handy because it is based on an interlocking male-female system made of tubes and connections (as presented in the following). Fittings – such as joints, elbows or T-pieces – are usually produced by injection-moulding.

4.3.1 Fittings

PVC connections for pipes are meant to realize the most branching operations as possible. Thus, there is a very impressive variety of forms and nature, from the most produced and commonly used to the most particular ones. Some project even require tailor made fittings. Different figures illustrate this diversity.
First, fittings differ by the *number of ends* they have: the simplest only have 2 ends, whereas some branching configuration require 3 (T-pieces), 4 or even 5 pipes to connect at the same point. Next, *spatial configurations* differ by the planes containing the pipes: some are coplanar, and other are orthogonal: the last allow

pipes coming from three spatial directions to connect. Then, a lot of different *nominal angles* are doable: the angle are available in a discrete range, from 0°(a straight socket connection) to 90°(right-angled elbows): nominal angles are 15°, 22°30, 30°, 45°, 67°30, 80°, 87°30, 90°.
They also differ by the nature of the ends and of the joints (as shown in Fig. 4.8):

- Plain-end: also defined as male end;
- Bell-end or socketed-end: we can also speak of female end. They connect with Plain-ends either with a simple push fit dilatation joints with rubber seals or with a particular sealing: it can be a welding (even though it is more used for PP pipes), but in general it will be a solvent cementing; further detail on solvent cementing is given below (Ch. 4.3.3).
- Flange-end: this method, originally used for metallic tubes, can be adapted to PVC pipes (Ch. 4.3.4).
- Threaded-end: these are used when a great flexibility is required because they mainly allow very easy disassembling. However, the PPFA states they should not be used for critical applications. Further detail is given in paragraph 4.3.5.
- Grooved-end: two grooved-ends can be joined by using a metallic clamp so that they be tightened and any leak be prevented.

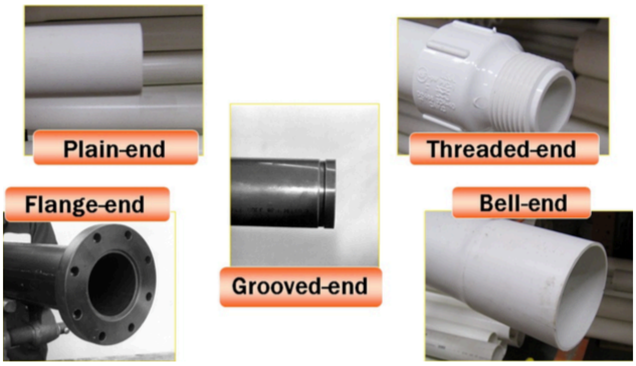


Figure 4.8: Different fitting ends types (Antaki, 2003).

Fittings can also be constituted by several elements: *assembled fittings* are formed from several injection-moulded parts assembled by clipsing or screwing, whereas *shaped fittings* are produced by thermoforming (Ch. 4.2), welding or solvent cementing from injection-moulded fittings or tubes. Finally, despite standards and regulations, irrevocable differences come from the different moulds used by each manufacturer, which result in small design details and dimensional variations. Other variants include the *radius of gyration* of the elbow, or the presence of a *reduction*: reduction allows to connect pipes of different diameters. One should never forget that these pipes are destined to fluid transportation, therefore many parameters such as 87°30

angles derive therefrom: in particular, they result from the orientation of the flow and from the minimization of online losses.
For fittings, some manufacturers recommend up to a 40% discount of the maximum design pressure with respect to the associated pipe.
To sum up the features described above, diverse types of fittings are shown on Fig. 4.11.

4.3.2 Tube ends

Prior observations about the nature of the ends and of the joints apply to PVC tubes. They have either both male ends (MM), or male and female ends (MF). In the first case, they require FF PVC sleeves to assemble. In the second case, pipes can connect directly, joining the male end of the first pipe to the female end of the successive one.

4.3.3 Solvent cementing

Main advantage of this type of connectivity is that often the joint is as strong or even stronger than the pipe of fitting. Then, no special and potentially expensive tool is required, and neither particular electric power nor heating procedure (open flames, torches, molten lead, or hot plates) which result in less likelihood for on-site injuries. It is very cost-effective. Though, one may be concerned that such connections are permanent: as a result, any leak may require a total disposal and replacement of the joint. They also take time on-site to be tested and validated.

4.3.4 Flanging

On the one side, flanging allows different piping material to be joined. It is used because of its ease to disassemble for inspection or maintenance and to repair any possible leak. Moreover the system can immediately be tested. On the other side, it is quite expensive and cumbersome. Furthermore, the working pressure is limited to 10 bars, which is a substantial limitation.

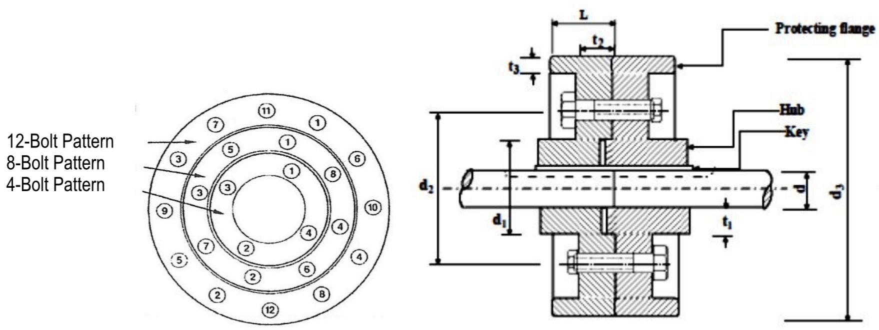


Figure 4.9: Different pattern exist for flanging, according to the project specification and diameters (Antaki, 2003).

4.3.5 Threading

Last noticeable manner to connect PVC pipes is threading: among advantages should be exposed the ease it provides to test the system, disassemble it and fix leaks. Though, main concerns regard their sophistication. They can only apply to sufficiently thick pipes. Once operating, threads constitute the weakest part of the piping system and *reduce working pressures by 50%.*

4.3.6 Possible association with other materials

PVC pipes can be associated to other materials. References are shown on Fig. 4.10.
Transition Joints. These tools are made to join cast-iron pipe to PVC pipes. Indeed, such pipes, because of their different normative framework and production processes, have dissimilar outside diameters.

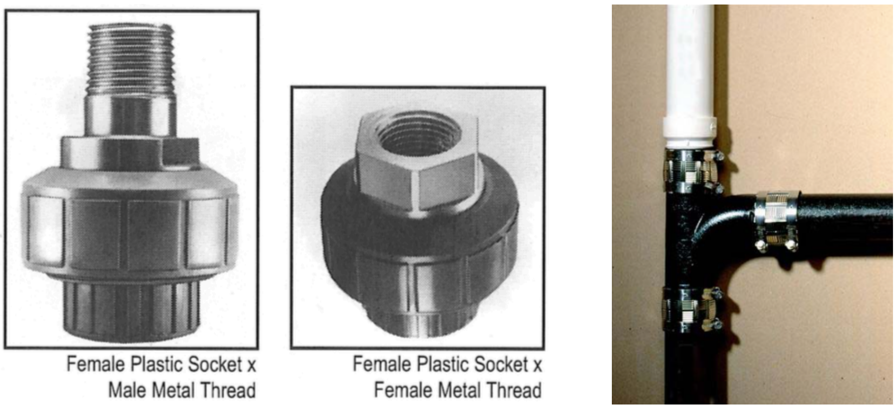


Figure 4.10: Transition joints (on the right) and threaded adapters (on the left) allow to associate PVC pipes with other materials (Antaki, 2003).

Threaded Adapters. They allow to connect a PVC pipe to a standard threaded-end pipe.
In the next part, only plain- and bell-ends fittings are used as they are the most easily supplied in specialized retailers and the most simple to connect.

4.4 Normative references

The same remark as in 3.9 applies. A census of both ASTM and ISO normative framework about PVC pipes can be found in annex. Main fields of application are distinguished.

4.5 Categories of uses

In agreement with the categories adopted by ISO and ASTM, the main uses of PVC pipes can be sorted as:

- *Soil, drainage, waste and vent pipes*;
  All these applications are non-pressure, so that it is possible to add rainwater evacuation and irrigation pipes. PVC-U and PVC-C are used, depending on the project typology.

- *Water supply pipes*: adducted water is under pressure at various temperatures; Such an application requires PVC-O, PVC-C pipes or barrier pipes (cf.4.6) even if PVC-U can also be used.

- *Gas supply pipes*: in most cases the use of PVC-HI is required;

- *Industrial pipes*: pipes need to resist aggressive fluids. According to the typology, PVC-U, PVC-C or PVC-HI are used.

PVC can also be found as a protective sleeve for telecommunication lines (Ch. 3.15), but in general PVC-P is used. All these applications regard aboveground and underground (According to the PPFA, more than 3/4 of PVC pipes are used for underground application) implementation of PVC pipes: this will be taken into account in the design of the piping system in conformity to the project data. These classes are the most relevant to be used as normative prescriptions impose common precise specifications to manufacturers. Therefore, despite the observed thousands of different denominations, all the different type of PVC destined to one of those will have sufficiently close properties to deal directly with those categories.

4.6 Geometrical characteristics

As said above, PVC piping systems have been used for more than half a century in many different applications. The main categories of uses are described in section 4.5. As a consequent, there is a great diversity of geometrical parameters. Each category of use underlies design specifications whose nature is often prescribed by a suitable set of regulations and standards (as in Ch. 4.4). Beside the nature of the plastic material and the different associative ways described in section 4.3, we can cite among the parameters of PVC systems:

- the diameter;

- the length of the tubes;

- the class of rigidity;

- the type of pipe wall.

Geometrical data is regulated for thermoplastics pipes by two norms:

1. ISO 161-1:1996 Thermoplastics pipes for the conveyance of fluids - Nominal outside diameters and nominal pressures - Part 1: Metric series;

2. ISO 11922-1:1997 Thermoplastics pipes for the conveyance of fluids - Dimensions and tolerances - Part 1: Metric series.

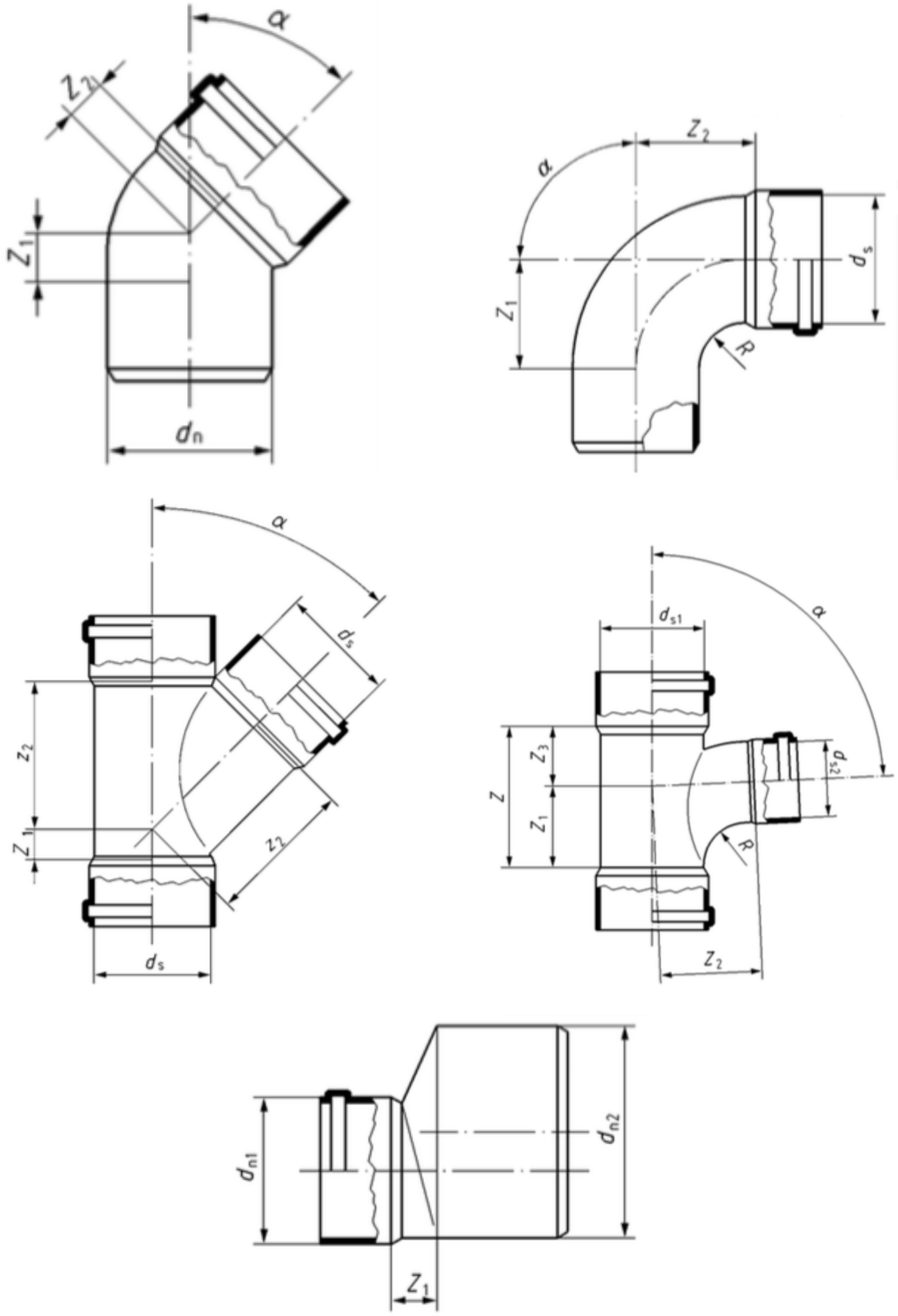


Figure 4.11: Different types of fittings.

4.6.1 Diameters

When dealing with diameters, main variables are:

- *Nominal External Diameter* D_N. It is the numerical designation of the size which is common to all components in a thermoplastic piping system[(4)]. It refers to the exterior diameter of the pipe. This value is a minimum requirement, which means that, for conservative reasons, real diameter has to be included in a range $[D_N\,; D_N \cdot (1{+}\epsilon)]$, with ϵ the tolerance, which is typically 0.2% to 0.3%;

- *Nominal Wall Thickness* e_N. It is the minimum wall thickness at any given point e_{min}. It is determined for each Dimension Ratio by Eq. 4.4, round at 0.1 mm.

- *Internal Diameter* D_i. It is defined by:

$$D_i = D_N - 2\,e_N \tag{4.1}$$

- *Average Diameter* D_m. Its expression isgiven by Eq. 4.2.

$$D_m = D_N - e_N = D_i + e_N \tag{4.2}$$

These numbers and the associated tolerances are not given in this study because they highly depend on the domain of application. One will only find typical values of nominal diameters are shown in Tab. 4.1 and Tab. 4.2.

D_N [mm]	32	40	50	75	80	90	100	110	125	140
Note	Plumbing Very widespread							Civil Works Available in technical retail		

Table 4.1: Typical values for nominal diameters (Part I).

D_N [mm]	160	180	200	250	315	400	500	630	800	1000
Note	Civil Works Available in technical retail					Civil Works Rare				

Table 4.2: Typical values for nominal diameters (Part II).

4.6.2 Available lengths

PVC pipes are extruded and are generally available in: 2 m, 3 m, 4 m, 5 m, and 6 m straight lengths. Other lengths are generally tailor made. Available lengths depend on the domain of application of the pipe and of the manufacturer.

[(4)] other than flanges and screw-thread elements

4.6.3 Type of pipe wall

PVC pipes either have:

1. Solid walls or compact walls are tubes or fittings whose internal and external surfaces are smooth and which have same composition along the thickness of the wall(5). It means that the pipe is simply extruded from amorphous PVC, as explained in section 4.2. Bi-axially oriented PVC (PVC-O) enter this category.

2. Corrugated walls are solid wall whose shape provide more flexural flexibility, as the ripples are along the hoop direction.

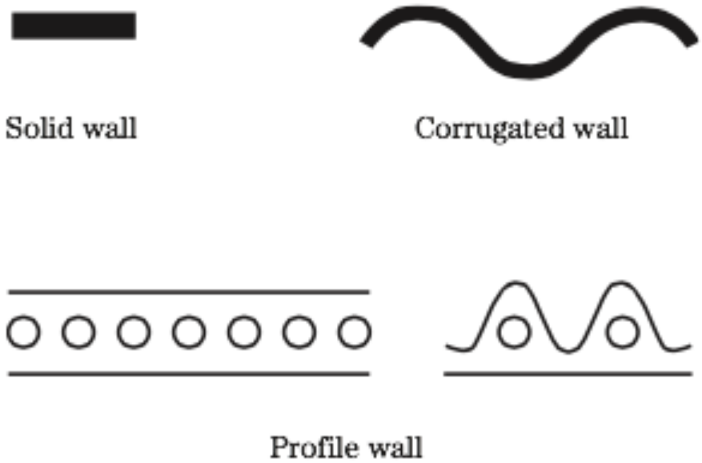


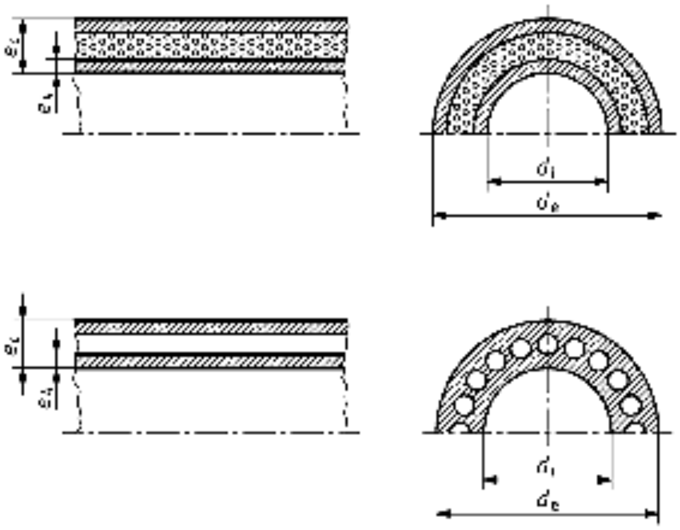
Figure 4.12: Main types of walls.

3. Structured walls. It is possible to find under this denomination convoluted tubes or profile walls, whose external and internal surfaces are smooth and connected by an intermediate layer or axial ribs (type A1), radial or spiral ribs (type A2), or corrugated Their production is regulated in Europe by NF EN 13476-2 of September 2007, from which Fig. 4.13 is derived. They offer a better resistance to internal pressure and are more flexible.

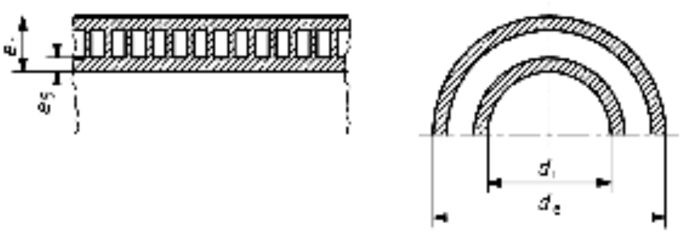
4. Barrier type wall or Multilayer. Several cylindrical layers compose the pipe. In the case of the barrier type wall, a flexible metallic layer(6) is inserted between two external and internal solid layers so as to provide additional protection for the fluids passing through the pipe (generally drinking water). Production is made by extrusion.

(5) see definition in NF EN 1401-1

(6) Typically in aluminium.



(a) Top and center.



(b) Bottom.

Figure 4.13: Types of structured-walls for PVC pipes.

4.6.4 Classes of rigidity

An important parameter that defines the mechanical abilities of a pipe is its class of rigidity, or ring stiffness This ability accounts for its resistance to internal pressure and to crushing. Several abbreviations are used to identify such a class: SN (Stiffness Nominal), DR or SDR (Standard Dimension Ratio), Sch (Schedule).

Denominations. The number which follows the letters SN represents, at a given speed, the value of the necessary force to crush the pipe of 3% of its internal diameter. It is expressed in kN/m^2 (equivalent to kPa). It enters the European normative framework. Most produced standards are: SN2, SN4, SN8 and SN16.

Schedule. The classical American framework for pipes deals with schedules this number indicates the approximate value of the ratio:

$$Sch = 1000\,\frac{P}{S} \tag{4.3}$$

where

- Sch = schedule
- P = service pressure (Pa)

- S = allowable stress (Pa)

In the US, schedule where originally applied to Welded and Seamless Wrought Steel Pipes [7] (from Sch/10 to Sch/160) and Stainless Steel Pipes [8] (Sch/5S, Sch/10S, Sch/40S and Sch/80S).
SDR. The designation SDR is internationally used: it is the ratio between outside diameter D_N and wall thickness e_N. Literature also mention SIDR, which considers internal diameter:

$$\begin{aligned} SDR &= \frac{D_N}{e_N} \\ SIDR &= \frac{D_i}{e_N} \\ SDR &= SIDR + 2 \end{aligned} \tag{4.4}$$

It is worth note that the function SDR(D, e) lies theoretically in the interval $[2\,; +\infty[$ because the thickness e, whose exterior limit is D, can not exceed the radius r = D/2. For example, the Belgian regulation BENOR states the following equivalences for underground PVC pipes:

- SN2 or SDR 51 (for 1 m-to-3 m backfill);
- SN4 or SDR 41 (for backfill of thickness minor to 1 m or major than 3 m with traffic load);
- SN8 or SDR 34 (for important loads).

For small diameters, thickness of a SDR range are not defined anymore by Eq. 4.4 because it would lead to number minor to 1 mm. However, data is exhaustively reported in the corresponding European norms. For all ring stiffness numbers, the higher the value, the stiffer the pipe.
In conclusion, this paragraph has established the main parameters of PVC pipes. In the following, only compact-wall pipe will be used as they are the best compromise between low price and resistance to flexure. Pipe will be referred to by their nominal external diameter and standard dimensional ratio.

4.7 Situation of the market

The market of PVC piping system is divided according to the normative fields defined in section 4.5. A exhaustive study of each of these is not possible here. General features will solely be enlightened.
As concerns the price with respect to other materials, here they are presented the results of an engineering report of 2006 in the city of New York. This report compared the different costs of metallic and plastic plumbing systems in a 12-floors residential building. It has taken into account technical details of implementation of

[7] Terminology from ANSI/ASME B36.10
[8] Terminology from ANSI/ASME 36.19M

a piping network, considering specific limits and needs of each type of piping system. The reasoning is based on an equivalence of performances: diameters, schedules and fittings are adapted from a system to another if needed.

Item	Total Material Cost	Total Labor (hours)
ABS Plastic Pipe Installation	$19,998.13	2008.87
PVC Plastic Pipe Installation	$19,536.60	2003.35
Cast Iron Soil Pipe Installation	$121,217.57	2736.88
Difference Between PVC and Cast Iron	$101,680.97	733.53
Percent Savings Using Plastic Pipe	83.88%	26.80%

Figure 4.14: Labor and discounted cost for Drainage, Waste, Vent piping installation.

Item	Total Material Cost	Total Labor (hours)
CPVC Plastic Pipe Installation	$9,830.27	1835.14
CPVC Plastic Pipe and PEX Tubing Installation	$19,305.68	525.22
Copper Tubing with Solder Fitting Installation	$28,397.52	1811.42
Copper Tubing with Press Connect Installation	$30,837.46	1402.04
Galvanized Steel Pipe Installation	$57,397.40	2361.65

Figure 4.15: Labor and discounted cost for Water piping installation.

For the Drainage, Waste and Vent (DWV) network are considered PVC, ABS and cast-iron pipes, whereas for the Water network are compared PVC-C, copper and galvanized steel pipes.

Using PVC pipes instead of metallic pipes (copper or galvanized steel tube) would spare 75% of the cost of the installation and almost 40% of the labour time. Therefore, PVC is much more competitive than steel tubes for residential piping networks. Therefore, PVC has shown itself economical and time-saving when used as pipes.

In addition, the price of PVC piping systems is exponential of the diameter, as shown in Fig. 4.17. After $D_N = 200$ mm, prices explode as production volumes decrease. Therefore, this diameter is a delimiter below which a designer should remain so as to maintain relatively low costs. Prices also increase with SDR, as shrinkage is less favourable and input quantity of material is greater.

Riser and Main Material	Material Cost	Labor
Plastic Pipe Installation	$38,842.28	2528.57
Metallic Pipe Installation	$152,055.03	4138.92
Difference Between Plastic and Metallic	$113,212.75	1610.35
Percent Savings with Plastic	74.46%	38.91%

Figure 4.16: Comparison of labour and discounted cost for plastic and metallic piping systems.

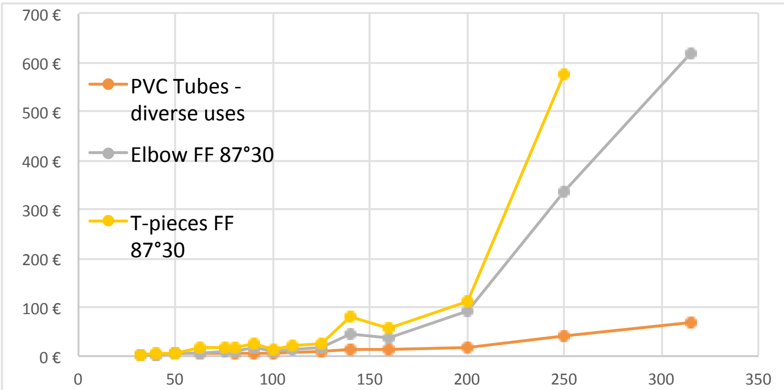


Figure 4.17: Variation of the price of PVC piping systems according to increasing diameters.

4.8 Other tools and material

4.8.1 Clamps

Several clamps are used to connect PVC pipes, as shown on Fig. 4.18:

- *Screw leg* metal clamps for larger diameters, to create a fixed point;

- *lyre* clamps, clipped for small diameters: they maintain the tube loosely. Can be in plastic (PVC) or in metal.

Figure 4.18: Screw leg metal clamps (left and center) for large diameters and lyre clamps (right) for smaller pipes.

Other types of clamps are not used for pipes because they do not provide sufficient rigidity (cf. fig 4.19.

Figure 4.19: Screw leg metal clamps (left and center) for large diameters and lyre clamps (right) for smaller pipes.

4.8.2 Valves

Pipes need to be regularly inspected. Flow inside is regulated by the degree of aperture of the valves. Of course, for pipes they have a crucial importance. Like fittings, they are injection-moulded. Many types exist:

- ball valves (also multiport valve);
- butterfly valves;
- spring-, ball-, and swing-check non-return valves;
- diaphragm valves;
- knife gate valve;
- globe valves;
- pressure relief/reduction valves.

Figure 4.20: Examples of valves: ball valve, diaphragm valve and knife gate valve.

4.8.3 Supports

Fig. 4.21 show such systems used to fix, clamp or simply support pipes, for example on a façade or under a roof.

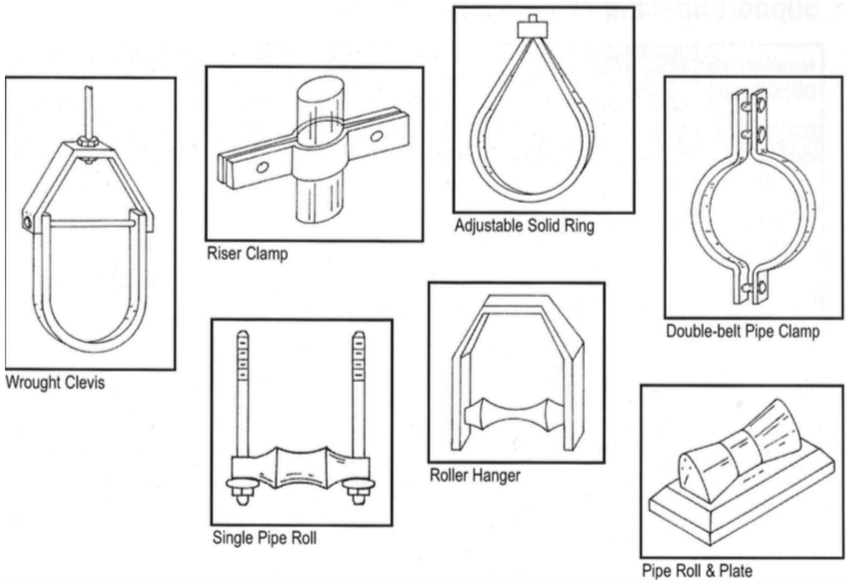


Figure 4.21: Various supports for pipes (Antaki, 2003).

4.8.4 Other accessories

Finally, other accessories are always helpful when dealing with PVC pipes: solvents - to seal and connect pipes and fittings -, cleaners, glues, clips, backing rings, and gaskets.

4.9 Concluding remarks

This chapter has shown the great interest that plastics can have for structural applications. In particular, PVC is one of the most interesting among them, because of its relatively good mechanical properties, excellent durability and low weight. Its costs are much lower than other construction material and it is already more competitive than steel for piping systems. Indeed, the large number of PVC resin and product manufacturers supports a very competitive market (220,000 t of PVC tubes and 25,000 t fittings are produced in 2010 in France, according to the PPFA (Antaki, 2003)). Their main advantage remains their behaviour on-site: they do not need maintenance, are easy to install and provide modularity thanks to its fittings components. Their use as formwork ensues naturally from theses products.

As a conclusion, the following sentence of the British Plastics Federation (Booth and Robb, 1968), applied to prefabricated and modular systems, is perfectly adapted to PVC as pipes.

The future will see the growth of intelligent buildings and methods such as prefabrication which will move work away from construction sites and into factories. Their resistance to corrosion, light weight and strength make the potentiality of load bearing structures as opposed to architectural features a possibility.

Chapter 5

Attempts to create a PVC bearing structure

The material PVC and its products have been properly defined in the previous chapters. This chapter states the different conception that have been thought to implement PVC. When the principles of conception have been fixed, scale models have been realized to understand better the effective behaviour of the structure. A calculation with a full size model has been realized, giving to PVC tubes a full structural role, removing intermediary supports.

5.1 Principle of the conception

The chosen conception is a bridge whose deck leans on vertical columns. The latter are connected to a parabolic cable, carrying the load to the supports, as shown on Fig. 5.2.

Figure 5.1: Principle of the conception.

Such a structure is *efficient*: it structurally behaves as an equilibrium of normal compressive – for the deck – and tensile forces – for the cable. Bending effects are small and only due to imperfect geometry and localized variable loads. The parabolic shape is adapted to optimize allocation of the efforts as it approaches the funicular curve of loads under self-weight and uniform loading. All plastic elements are under compression which avoids dismantlement of the plastic elements. Assembling is

relatively simple because plastic-to-plastic connections are made thanks to apposite elements and plastic-metal connections are limited. Then, the lower struts rigidify the vertical stiles (Contrarily to the model presented in the first chapter, whose height is determined by the choice of the number of diagonals). Design is flexible by the possibility to adjust theoretically the height as it is decorrelated from other parameters such as the number of vertical struts.
However, the form is strongly influenced by the shape and the deformability of the cable: therefore it will be very *sensitive to localized effects*.
For what concerns prestressing, the structure is wall adapted as the plastic elements are meant to be compressed. Vertical load is carried by the cable, compressing the deck horizontally and the columns vertically. Prestressing could even be imposed as a positive initial deflection, taking advantage that the great flexibility of the PVC structure. The counterpart of this is the major *buckling sensitivity* of compressed chords, especially the deck under strong compression.
Beside being *elegant* and letting the deck completely open, it also seems to be a very simple structure to implement tube and fitting assemblies, with a cable to be passed through.
Finally, contrarily to an arch, no clamping is required a the supports for stability: the structure is *simply-supported*. It is only necessary to ensure freedom of longitudinal translation on a support to allow for the deck to be compressed.

5.2 Scale model

A scale model has been made to gain more insight into the behaviour of such a structure and into its on-site construction.

5.2.1 Components

It is meant to be approximately a 1:4 - 1:5 scale model. It has the following dimensions:

- Length $L = 5$ m;
- Width $w = 0.5$ m;
- Maximum Height (at midspan) $H = 0.8$ m;

For the construction, tubes and fittings of thickness 2 mm and diameter 40 mm have been used: they are the most furnished piping systems in retail because they correspond to plumbing equipment. Cables are constituted by polypropylene ropes. Again, these have been used for they are practical and use to use.
Tab. 5.1 details the main mechanical characteristics of PP, with respect to both PVC and steel, according to commercial documentation. PP is far more deformable than steel. As deformation of the scale model is strongly connected to cable deformability, the scale model is expected to be quite deformable.

Figure 5.2: Material for the scale model.

Characteristics	Unit	**PVC**	**PP**	**Steel**
E	[MPa]	3	1.3	200
ν	[-]	0.5	0.3	0.3
Specific weight	[kN/m^3]	14	6	78.5
f_y	[MPa]	40	21	450

Table 5.1: Main characteristics of PP for design with respect to PVC and steel.

5.2.2 Construction

First, tubes are cut at the right length, taking into account that the deck elements and superior crosspieces have uniform lengths whether columns and inferior crosspieces have variable lengths. The non-zero length of fittings is subtracted from the length of the different tube elements.
Then, it is necessary to drill holes in the fittings to make the cables pass. Their position on the elbows is coherent with the sketch of the cable passing through each of the fittings so as not to generate flexure. The cables are not fixed to the fittings in this model as it would be too complicated.
The footbridge is built with the deck leaning on the ground. Fittings are not sealed between then(1). Crosspieces are alternated with columns along the deck because available fittings don not allow more than 3 tubes to connect at a same node. Cables are threaded into the fittings in the apposite holes and fixed at the supports. The

(1)No glue is used to ensure continuity between the fittings.

model is then turned and set on its supports. Its very low weight (10-11 kg) makes it mobile even by a single man.

Figure 5.3: Footbridge set with deck on the ground.

Figure 5.4: Bracing system.

Finally, bearing cables are tensioned to get a zero deflection at midspan. Bracing is set up as in Fig. 5.4. The fittings have 87°30 angles so that they have to be disposed in a symmetrical manner with respect to the longitudinal axis of the footbridge to avoid torsion of the bridge.

5.2.3 Hypothesis

The behaviour of the bridge is very hypothetical. Its constitutive materials (PP, PVC) are poorly known and in particular the mechanical abilities of their fittings (stiffness, flexibility, plastic hinge) and their mechanical limits and modes of failure (in tension, in compression, under bending, at rupture). Therefore, 3 situations are considered, alongside with 3 levels of hypothesis:

- **S1 - Perfect clamping**. The first reasonable assumption is to consider a perfect clamping for all fittings, which means no differential rotation would be allowed between connected tubes. Though, this hypothesis seems very optimistic. On the one hand because it is observed that the columns (it is important underlined that the columns are the longest elements) are rather mobile to some extent. On the other hand, because it is conceivable that, under a heavy load, a perfect clamping would generate localized moments, potentially sufficient to break them (or have them plasticized).

- **S2 - Articulation of the columns with respect to the deck**. The appearance of the footbridge under its own weight (that is to say under moderate or even weak forces) leads to questioning the hypothesis of perfect clamping. It can be assume an articulation as the columns seems rotationally quite mobile.

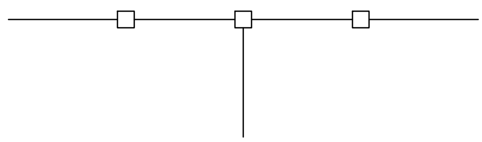
- **S3 - Articulation of the deck with respect to the columns**. This questioning can be done in two steps, the effect of which is to be evaluated: articulation at the level of the columns (where the most important moments occur when the deck is loaded - S3) and at the level of the crosspieces (S4). Obviously, the clamping is replaced by an stiffened articulation, necessary for the stability of the model on Karamba. The rigidity is expressed in terms of kg.m/°: for 1kg.m/°, a force of 1 kg (10 N) exerted at 1 m of the tee deforms it by 1°. Finally, the effect of a greater flexibility of the fittings in the direction of will be analysed to evaluate the sensitivity of the model to this parameter.

The different hypothesis are presented in Fig. 5.5, where a square stands for a clamp, a circle for an hinge. A longitudinal view is drawn, showing the deck elements and a column. Crosspieces are out of plane.

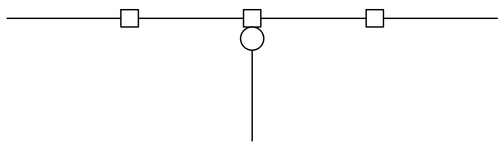
5.2.4 Loading

A step-by-step loading test of the footbridge is realized to identify the correct properties with respect to the previous hypothesis. The midspan deflection is measured and confronted to the increase of the loading. Loads are paper blocks, whose weight is well known. With available A3 and A4 formats, blocks respectively weight 2.5 kg and 5 kg. The amount of the load increase is 2.5 kg, that makes necessary a substitution of 2 A4 by 1 A3. This action will generate a small increase of deflection(2) due to plasticity because they actually consist of local unloading-reloading cycles.

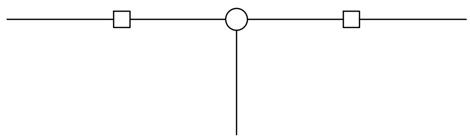
(2) As can be seen on Fig. 5.8



(a) Level S1.



(b) Level S2.



(c) Level S3.

Figure 5.5: Different levels of articulation of the fittings: S1, S2, S3.

First loading. It was performed on 5 different points. The measurements were made in 2 different positions, to detect possible torsional movements:

- at the level of the deck on one side of the model;
- in the center of the struts in the lower part.

The plates used to set the loads are large (37.5 cm wide x 80 cm long) with respect to the dimensions of the deck: distance between two consecutive crosspieces is 50 cm, and distance between a column and a crosspiece is 25 cm. Width of the footbridge is 50 cm. As a consequence, setting the center point of the plates on the top of the columns made their edges leans on the crosspieces. The real point of application results be misplaced. In addition, a first unforeseen ruin occurred (the tubes are unclipped at the supports) which made it necessary to reinforce the model before reloading.

Second loading. It was carried out on 4 different points, in correspondence of the spacers, to load the columns correctly. The unloading was monitored and the corresponding deviations are reported. The results of the calculation were obtained for a load Q on 5 plates. Therefore, the load will be extrapolated to the total load parity so that $5Q = 4Q'$ and thus $Q' = \frac{5}{4}Q$.
Loading was stopped when the model began to become very unstable and threatened to buckle laterally. A lateral instability of the footbridge and cracking noises at the joints could be observed : they are due to plastic-counter-plastic frictions at the fittings.

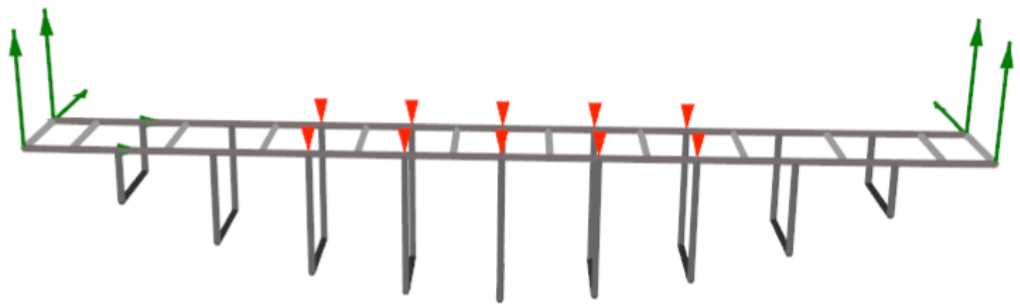


Figure 5.6: Disposition along the footbridge of the 5 points of loading.

5.2.5 Results

The results of the loading test are presented in Fig. 5.8 for loading and unloading phases. Max deflection v_{max} reached 24 cm, at midspan (see Eq. 5.1).

$$v_{max} \approx \frac{L}{20} \tag{5.1}$$

Residual deflection v_{res} after unloading is 13 cm, which is 50% of max deflection:

$$v_{res} \approx \frac{v_{max}}{2} \tag{5.2}$$

The total load on the deck at the maximum loading point was:

$$Q_{tot} = 4 \cdot Q = 25\,kg \cdot 4 = 100\,kg \tag{5.3}$$

which is far more than the weight of the bridge G.

$$Q_{tot} \approx 10G$$

Loading is not linear because of the large displacements. A first stage can be noted, for which deflection increases with a gradually decreasing slope. The cable deforms to adopt a form closer to the funicular shape. The design shape is the funicular of an uniform load, that is of a load distributed uniformly on all the columns. Loading is then globally linear, exception made of local increases mentioned in section 5.2.4: the new funicular shape is then loaded classically.

In parallel, the model by conform implementation of the load has been step-by-step computed on the finite elements software Karamba: a 3D geometry of the model is built, and converted into a computational model of beams. By increments of 1 kg by plate, load has been increased to the maximum of 25 kg resulted from the test. For S2 and S3 situations, different flexural rigidities have been implemented for the articulated fittings, from 0 kg.m/°to infinite rigidity[(3)]. Computed deflections for situations S2 and S3 described in section 5.2.3 are shown on Fig. 5.9 and Fig. 5.10. In particular:

[(3)]Infinite rigidity is equivalent to a perfect clamping of the fittings.

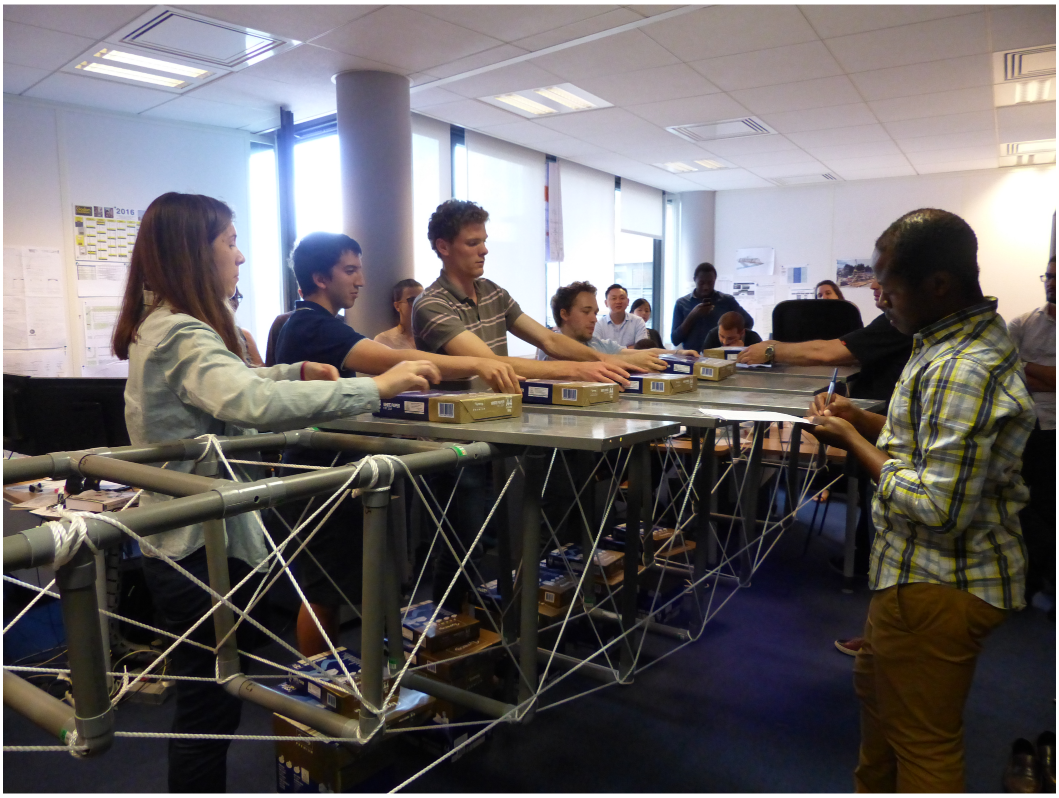


Figure 5.7: Loading with paper blocks.

- For articulated columns, the deflection is clearly linear of the load, whatever the rigidity be. Measured deflection is close of calculated deflection for zero rotational stiffness.

- For the situation No.3, the initial non-linearity decreases with the rotational rigidity. A second phase is linear and almost independent of the stiffness. Deflection from the test hhas a loading path comprised between those of stiffness 0.01 and 0.1 kg.m/°.

For each of the following curves, the maximum deflection is stored and plot on logarithmic graph of figure 5.11 according to the situation (S2 or S3) and the rigidity (from 0 kg.m/°for a fully articulated behaviour to 10^6 kg.m/°, considered clamped behaviour) to draw the variation of the maximum deflection according to the rigidity of the articulations. For elevated values of stiffness, results may be influenced by ill-conditioning of stiffness matrix. This figure clearly confirms that range of the hypothetical rotational stiffness of the fittings. I other words, assuming that a rigidity can be defined for such fittings, the procedure and subsequent logarithmic graph allow to determine it quite precisely by intersection. Assessment on several scale model would be necessary to state this.
From the previous graphs, it can be deduced that the actual behaviour of the fittings is closer to situation S3 than to situations S1 and S2. As a consequence, for the

structural analysis of this statical scheme, one shall take into account for the deck articulations in correspondence of the columns.

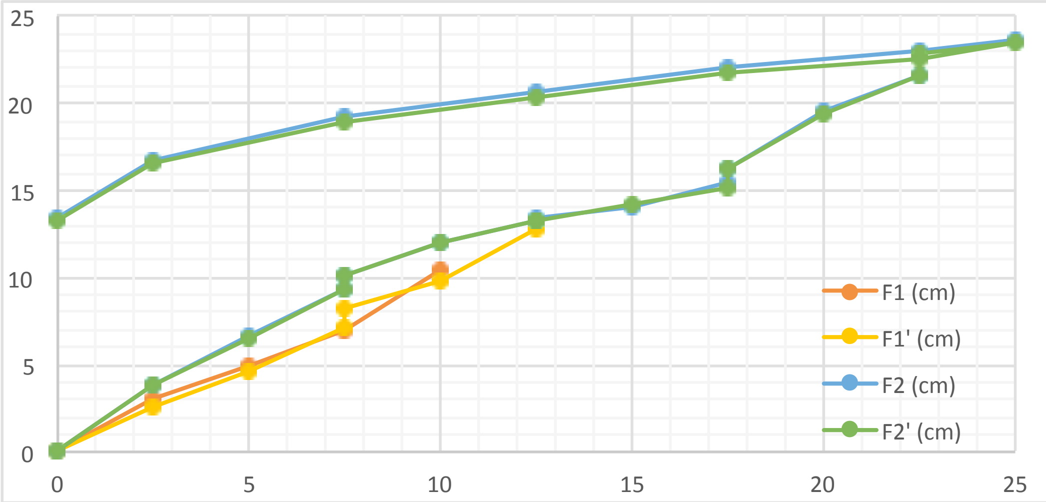


Figure 5.8: Measured deflection in cm as a function of the load by plate in kg.

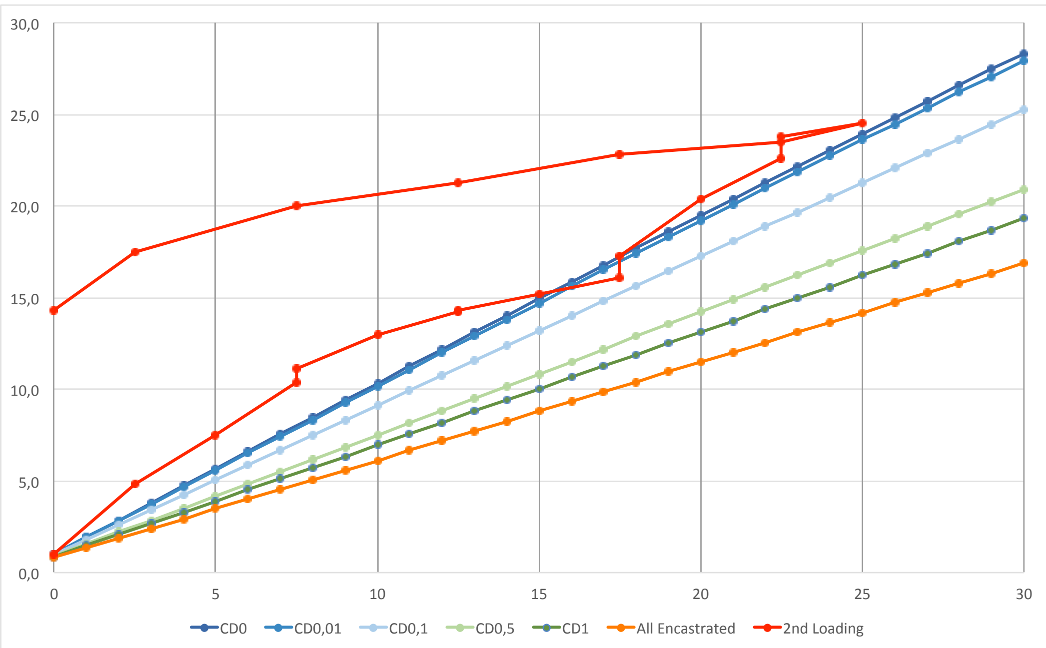


Figure 5.9: Computed step-by-step deflection compared to measured deflection, at midspan for situation S2 and rigidities varying from 0 to 1 kg.m/°.

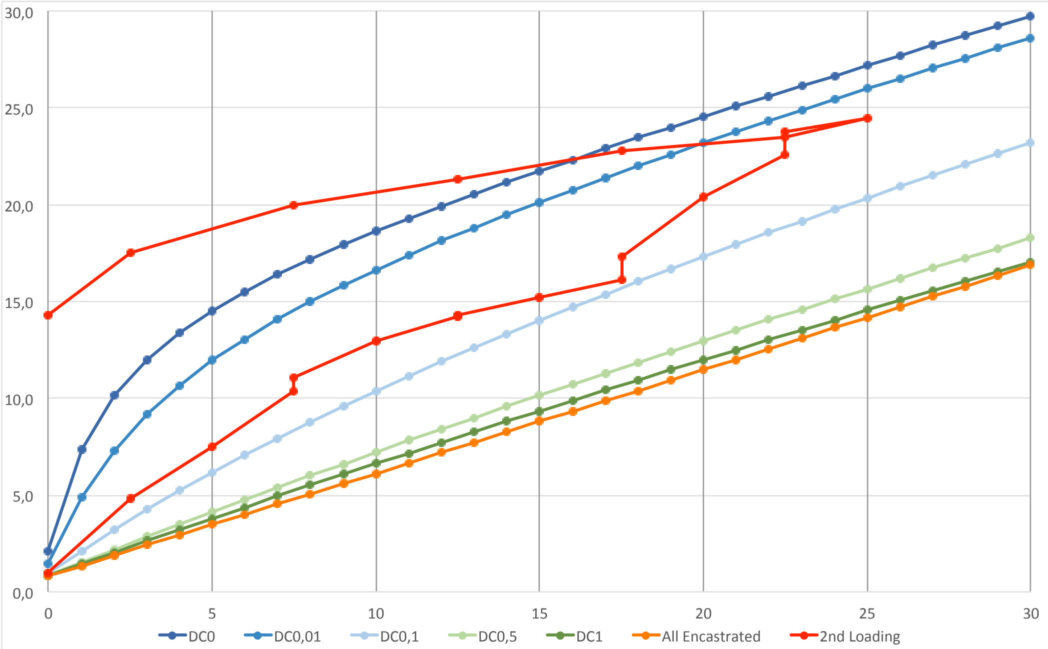


Figure 5.10: Computed step-by-step deflection compared to measured deflection, at midspan for situation S3 and rigidities varying from 0 to 1 kg.m/°.

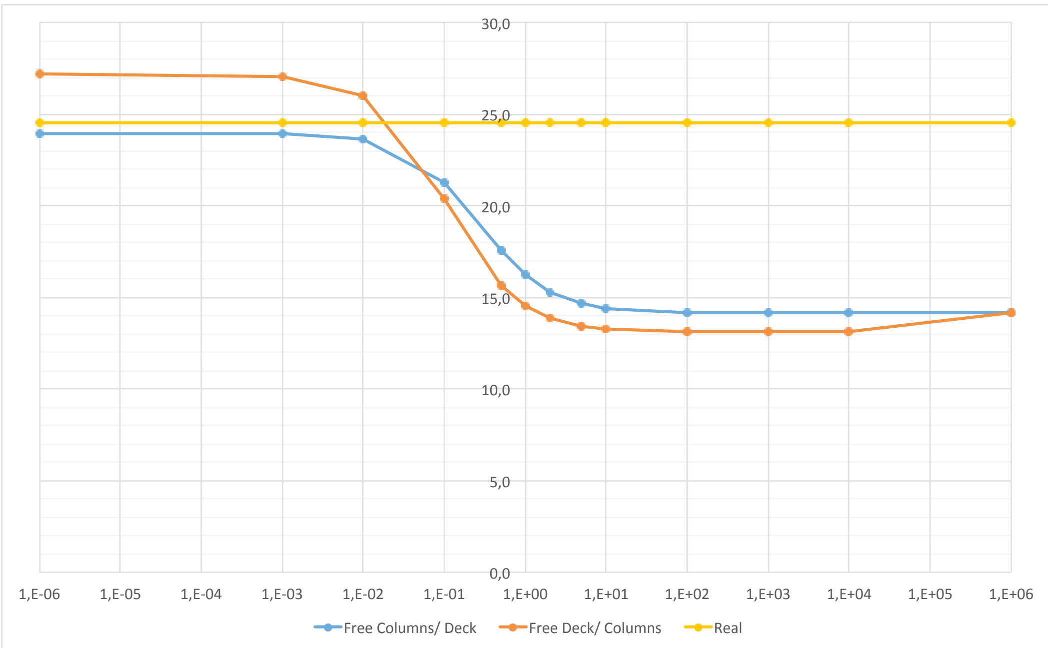


Figure 5.11: Computed maximum deflection at midspan as a function of the rigidity of the articulations.

5.2.6 Structural conclusions

As shown on Fig. 5.4, bracing is constituted by ropes "stitched" along the bridge, so that their successive parts are alternately in compression and then in tension. The compressed part obviously buckles as a rope is classically unable to withstand compression. Thus it relaxes the parts in tension. As a matter of fact, bracing becomes ineffective.

Figure 5.12: Sewing of the bracing rope along the longitudinal axis.

Moreover, the tension of the ropes was meant to provide a friction resistance against any longitudinal displacement along the cable: in particular, it would have restrained rotations of the columns, whose rotational rigidity is low. Therefore, the base of the columns slightly moves along the cable. The rotations of the assemblies and the horizontal translations of the columns along the cable are not completely prevented by the present practical arrangements.
Friction at the level of the structure creates plastic effects: the deflection becomes non-linear of the load, and is non-zero after unloading.
Maximum admissible loading was about 100 kg. Given its width (0.5 m) and its length (5 m), this load represents an equivalent surface load of 40 kg/m^2, which is very far from the 500 kg/m^2 objectives that a 1:1 scale model should able to support according to Eurocode. Several factors are responsible for this deformability:

1. Since the fittings do not seem to be stiff enough to consider them as clamped, the presence of 19 potential hinge along the deck[(4)] considerably reduces the stiffness of the deck. It can be shown on Fig. 5.19: even without loading, the scale model can be waved. Therefore, to a solicitation does not correspond a single configuration because of plastic effects.

2. The bearing cables are made of PP (E = 2 – 3 GPa): it is a very flexible and deformable material, which amplifies these deformations. Using steel would decrease the axial deformability of the cable and consequently the deflection.

3. Bracing has to be set independently for each members so as to make it effective.

4. The scale model had severe stability default. Among them, it is worth note the alignment problems at the supports (as shown on Fig. 5.13). The cable is

[(4)] There are 10 crosspieces and 9 columns along the deck.

diverted by the feet of the seat used as a support. Then, even if it would have made construction quite less rapid, simple and economical, pipes and fittings need to be fixed rigidly between them to avoid recurring uncoupling. Plastic seal or metal screws are considered.

Figure 5.13: Alignment problems.

5.3 Structure at realistic scale

Taking into account necessary improvements that section 5.2.6 concluded, a second structure has been designed and calculated at a realistic scale.
The purpose of the second model computed is to resolve the previous problems and to make the PVC skeleton able to bear the self-weight of concrete: such as structure would allow to pour concrete in it directly in one phase. Concrete members are not reinforced with steel bars because the members are assumed to be compressed.

5.3.1 Main elements

Dimensions of the structure are indicated on Fig, 5.14. The diameter of PVC piping system has been set to 250 mm. Thickness is 6.2 mm, as stated in the brochure Nicoll[5].
Fittings. Crosspieces are connected directly on columns to reduce the number of fittings alongside the deck. Obviously, for compatibility reasons, an eccentricity e had to be imposed. In accordance with Fig. 5.15:

$$e = 191mm + 143mm = 33.4cm \qquad (5.4)$$

[5] Nicoll is a pipe supplier

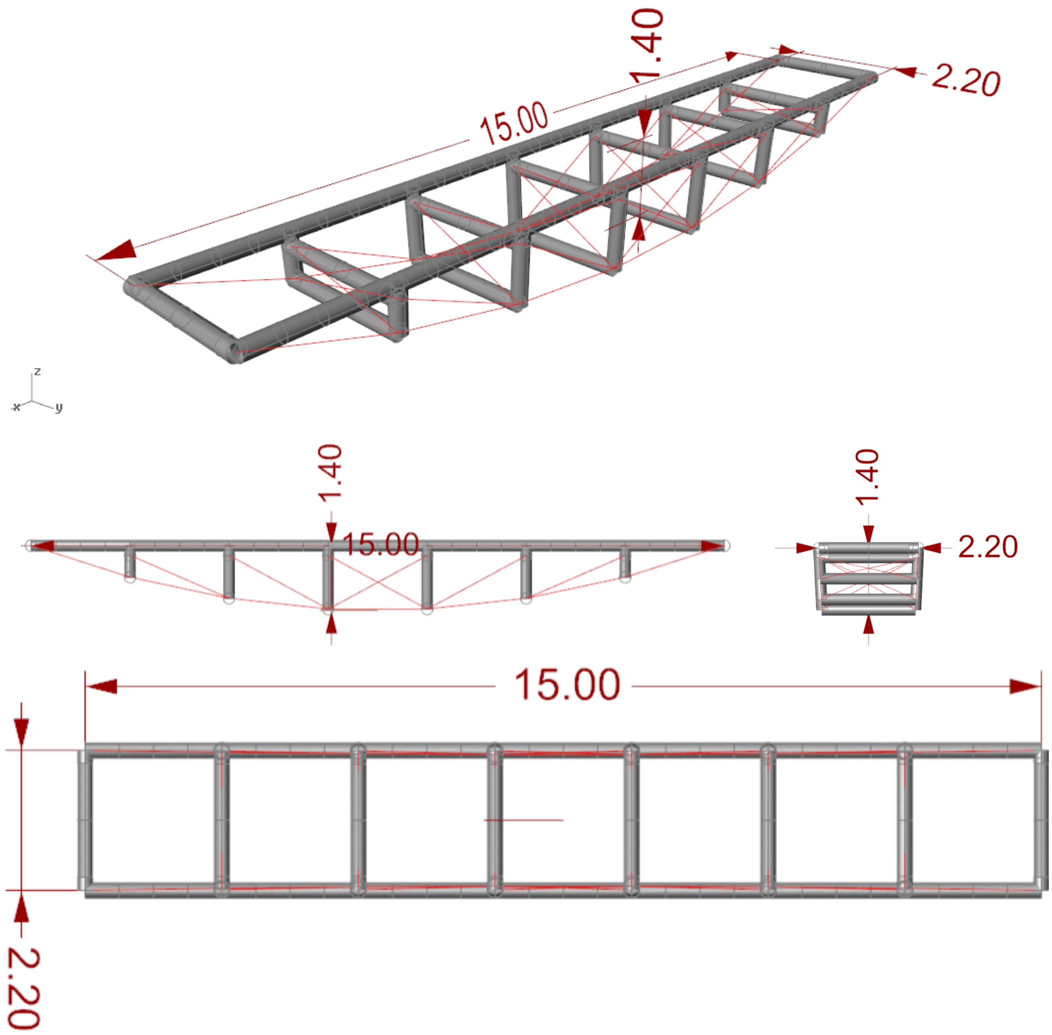


Figure 5.14: Geometry of the model.

Connections are made by assembling a FF tee between the deck and the column, and a MF tee between the column and the crosspiece. Angles are 87°30 because they are the most suppliable in retail.
The respective dimentions are listed in Tab. 5.2 and Tab. 5.3 (from Nicoll brochure).

Bending tests of the fittings were carried out on diameters 100 mm, 160 mm and 200 mm. The conclusions of the report of these tests have shown the increase of flexural stiffness with the diameter. For the diameters considered, a stiffness of 1 kg.m/°was a realistic order of magnitude for flexion out the plane of the fitting(6). It can reasonably be assumed that the stiffness would be lower if the flexion was exerted in the plane of the tee. Therefore, conservatively, a value of 1 kg.m/°is taken for tubes with a diameter of 250 mm.

(6)Conventions are fixed on figure 5.16

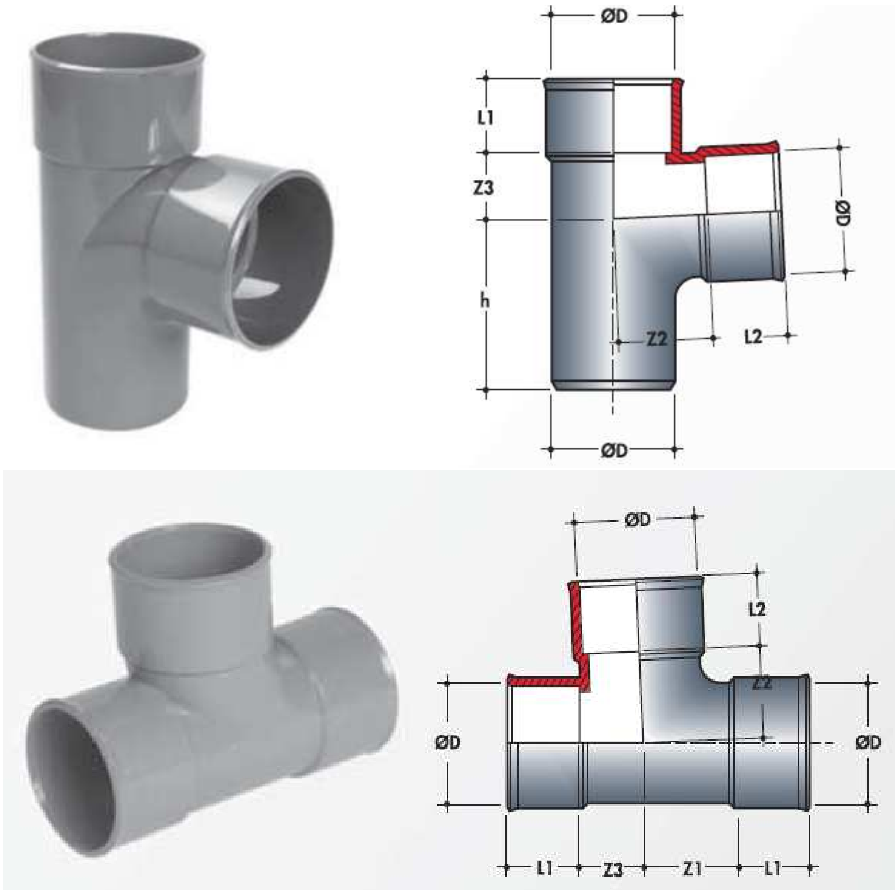


Figure 5.15: Fittings (mf and ff) in the brochure Nicoll.

Cables. Fig. 5.17 show the section of the cables used as bearing cables and bracing cables.

- *Bearing cables* are $\phi 30$ mm, typically used for lifting systems: 6x36 with textile core.
- *Bracing system* is constituted by $\phi 11$mm cables, 6x19 with textile core.

Data on resistance and maximum admissible efforts are presented in Tab. 5.4. Service effort N_s is calculated as the ultimate effort N_u divided by a safety coefficient of 3:

$$N_s = \frac{N_u}{3} \tag{5.5}$$

5.3.2 Phases and loads

Calculation is made in 3 phases, as required by the setting up procedure of the footbridge.

1. Loading under self-weight: a PVC skeleton is built, cables are installed, the structure is set on its supports. The amount of prestressing of the bearing cables needed to cancel deflection at midspan is determined and applied;

Fitting	D/d [mm]	h [mm]	z_2 [mm]	z_3 [mm]	L_1 [mm]	L_2 [mm]
BD18 (mf)	250	191	143	143	61	61

Table 5.2: Dimentions of mf-fitting.

Fitting	D/d [mm]	z_1 [mm]	z_2 [mm]	z_3 [mm]	L_1 [mm]	L_2 [mm]
BD188 (ff)	250	130	143	143	61	61

Table 5.3: Dimentions of ff-fitting.

2. Filling of the tubes by concrete: in addition of self-weight, each PVC member bears the weight of concrete that its internal volume would contain. A specific weight of 24 kN/m^3 is taken as a reference for concrete;

3. Variable loads: once concrete has hardened, it bears the additional load. Bracing cables are tightened. Therefore, geometry corresponds to internal section of the tube, material becomes a C25/30 concrete. A uniform pedestrian load of 500 kg/m^2 is applied, in accordance with requisitions of Eurocode 2. Hypothetical planking leans on crosspieces, therefore the load is transmitted to them, and then directly to the columns.

Actions are taken at SLS (Serviceability Limit State), that is with all coefficients equal to 1.

5.3.3 Criteria for verification

This section sums up the different checks the structure has to pass for each phase so as to meet equilibrium, stability and safety. Verifications concern the structure as a whole and specific members:

For what concerns the *Structure*:

- **Buckling Analysis**. A second order analysis by the software Karamba allows to determine the buckling coefficient of the structure (which is the coefficient f_s that should multiply all the imposed loads to make the structure buckle). It takes into account global buckling of the structure and local buckling of members. A safety coefficient $f_s = 3$ is taken. It applies to all the loads.

- **Deflection**. Deflection will be calculated mid-span. Criterion will be 0 at the end of phase 2, and L/150 at the end of phase 3: for this model, admissible deflection would be 10 cm.

at the same time, for the *Elements* is nesessary to perform analyses for:

Figure 5.16: Flexion of the fittings: in-plane and out-of-plane.

Characteristics	Unit	6x19 TC	6x36 TC
N_s	[kN]	23.6	178.7
σ_s	[MPa]	427	517
N_u	[kN]	61.7	536
σ_u	[MPa]	1280	1550

Table 5.4: Values for the resistance of cables.

- **Cables**. Efforts shall remain positive (tensile) and minor than admissible loads N_s defined in table 5.4 whatever the phase.

- **Tubes**. Verifications of the section of the tubes will concern the utilization of the material with respect to buckling limits and limit strengths, for all phases and with appropriate material properties:

$$util_{Rd} \leq util_{Ed} = 1 \tag{5.6}$$

  Moreover, one shall ensure that all tubes are compressed ($N < 0$), in order to avoid disassembling (for phases 1 and 2) and tension in concrete (for phase 3).

- **Bracing**. Similarly to the check of cables, efforts shall remain admissible in regards of limit load N_s.

5.3.4 Results

Results are shown on Fig. 5.18. Convention is:

- Green boxes stand for verified criteria;

- Orange boxes mean the criteria could not be verified because doubts exist on the resistance: it only applies to the flexural and compressive resistance of fittings in phase 2, when the PVC skeleton is structurally resistant.

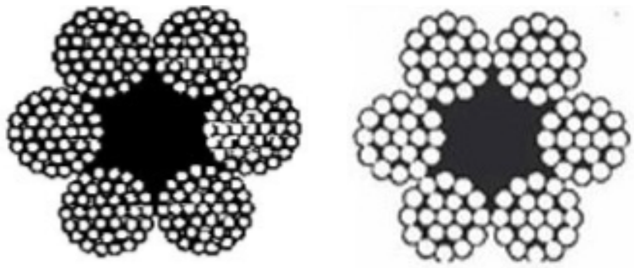


Figure 5.17: Section of the cable used.

- Red boxes are applied to criteria that is not checked.

CHECK	Phase 1	Phase 2	Phase 3
Buckling Factor	30.8	3.5	28.4
Disp L/2 [cm]			-3.6
min N cable [t]	0.65	5.82	14.29
max N cable [t]	0.7	6.08	16.09
Util tubes [%]	0%	40%	70%
min N tab [t]	-0.68	-5.85	
max N tab [t]	-0.67	-5.82	-13.71
min N column [kg]	-76	-558	
max N column [kg]	-5	-131	1115
min N crossp. [kg]	-41	-91	
max N crossp. [kg]	6	107	1452
min N bracing [kg]	-10	-4	-3
max N bracing [kg]	47	27	857

Figure 5.18: Criteria and results of the computation.

5.3.5 Structural conclusions

The second model is not applicable stricto senso because, of shown in Fig. 5.18. The following conclusions will concentrate on the limitations of the model and therefore on its necessary improvements.
First, it is worth noting that the deck is submitted to large compression efforts. This means small eccentricities of the deck could generate non-negligible parasite bending along it. Imposing a zero deflection at midspan is not a sufficient condition to avoid eccentricities along the axis of the deck and to ensure it be strictly. Eccentricities are created by differential deflection of the columns. Indeed, again, the parabolic shape of the structure is the funicular of uniform load. Though, at the end of the concreting phase, the structure is loaded by self-weight which is not uniform because of the presence of columns and of the load of the cables themselves. Moreover, given that no mechanical data could be found on the resistance to compression and flexion of PVC fittings, it is preferable to limit their structural role.

As a matter of fact, the procedure shall *add intermediary support between the columns* so as to prevent the PVC structure from bending.
Design has should that bottom crosspieces and some columns are in traction during phase 3[(7)]. Furthermore, definitive design footbridge shall allow to bear a vehicle along it deck. This means supporting important movable point loads along the deck and bending moments in concrete.
Reinforcement should be added in the concrete structure.
These structural modifications have to be implemented, especially since:

- ULS (Ultimate Limit State) coefficients shall be applied to design the structure properly. They will raise the solicitation and decrease the resisting actions;
- No load has been considered for planking: an additional uniform load will have to be imposed to the structure in phases 2 and 3 to take it into account.

Next chapter will present a definitive design of the footbridge.

Figure 5.19: Stability: the footbridge is too deformable.

[(7)] Phase 3 regards variable loads applied to the concrete structure.

Chapter 6

Presentation of the footbridge

After two attempts, a realistic model of a full scale footbridge can now be designed. Materials used and loads considered for its calculation are precisely referenced in this chapter. Then, the definitive phases of construction are described, taking into account the observations that concluded the previous chapter, so as to complete data about the footbridge.

6.1 Materials

The material propertie for each component of the footbridge is here realled.

6.1.1 PVC Fittings and Tubes

Characteristics of the fittings chosen are taken conservative: resistances are slightly decreased, actions are raised to account for the diversity of PVC types.

- **Diameter** $\phi = 250$ mm;
- **Thickness** $e = 6.2$ mm;
- **Standard Dimension Ratio** $SDR = 41$;
- **Young Modulus** $E = 2.8$ GPa (short-term);
- **Specific Weight** $\rho_{pvc} = 1.5$ t/m^3;
- **Elastic Limit** $\sigma_{adm} = 22$ MPa (short-term);
- **Supplier**: Nicoll(1)

Different types have been used: elbows FF and MF 87°30, tees MF and FF 87°30. Such angles have been used because they correspond to the most affordable and supplied fittings. Details and dimensions are shown on Fig. 6.1.

(1)It is important to mention the supplier as each has different mould and therefore distributed tees with varying dimensions.

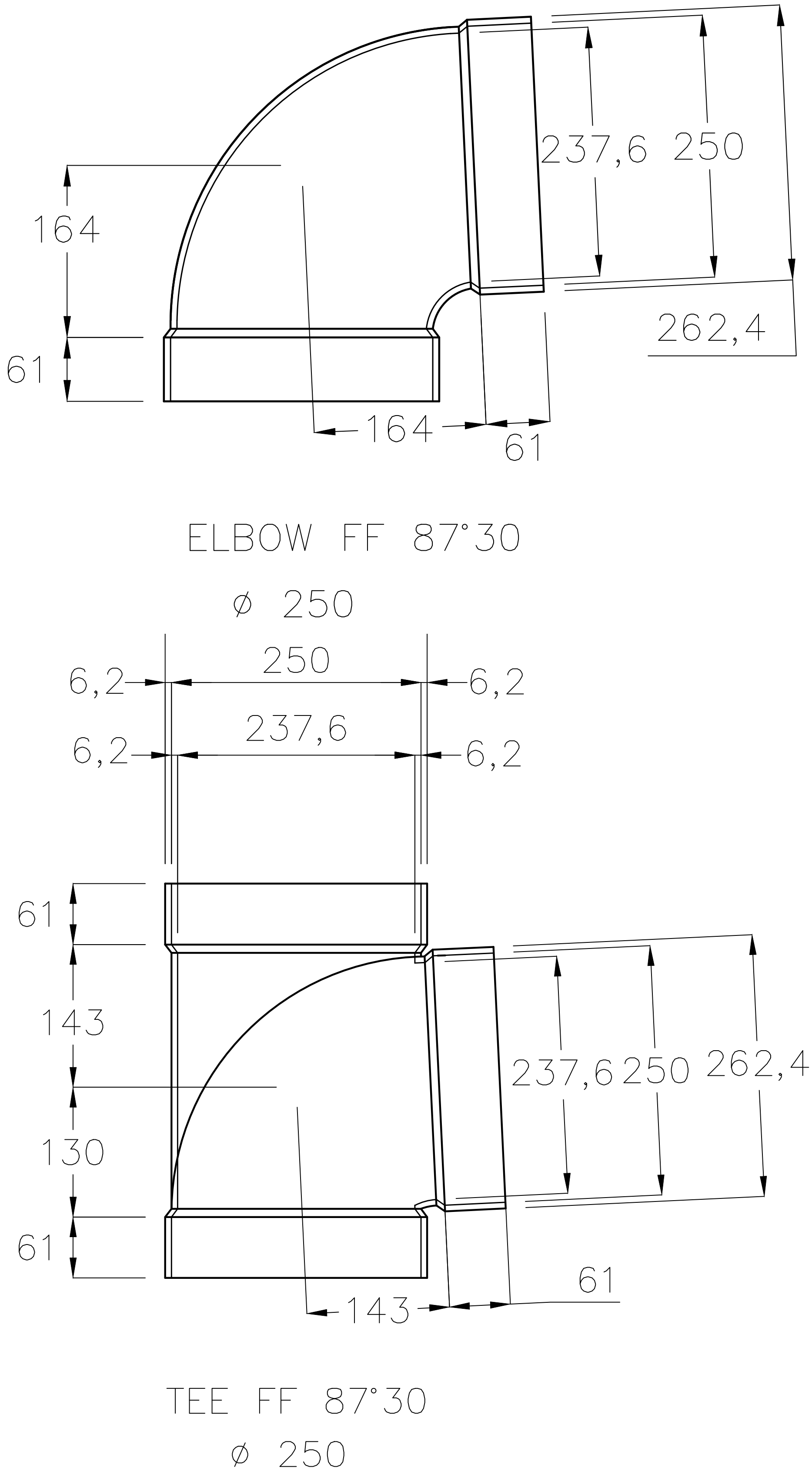


Figure 6.1: Dimensions of the fittings used.

6.1.2 Concrete

Concrete for pouring is a C25/30. Main properties are (UNI, 1992):

- **Young modulus** E_{st} = 31 GPa (short-term);
- **Young modulus** E_{st} = 10.3 GPa (short-term);
- **Poisson modulus** $\nu = 0.3$;
- **Specific weight** $\rho_c = 2.5$ t/m^3 for normally reinforced concrete;
- **Characteristic compressive concrete strength** f_{ck} = 25 MPa;
- **Mean value of concrete compressive strength** f_{cm} = 33 MPa;
- **Mean value of concrete tensile strength** f_{ctm} = 2.6 MPa;
- **Partial safety factors for concrete** $\gamma_c = 1.5$;
- **Coefficient taking account of long term effects** $\alpha_{cc} = 0.85$

A *self-compacting concrete* is used so as it be able to flow in the structure and fill the spaces between reinforcing nets.

6.1.3 Cables

Cable models are taken into the Teci brochure. Bracing are not installed on the definitive model because in the attempts, they were set to limit deflection of the PVC structure. Definitive structure is now regularly supported.
Classical properties for high-strength steel for pre-stressing are (UNI, 1992):

- **Young modulus** E_s = 205 GPa
- **Specific weight** $\rho_s = 7.85$ t/m^3;
- **Failure stress** f_{ptk} = 1860 MPa;
- **Characteristic stress at 0.1% total strain** $f_{p(0,1)k}$ = 1640 MPa;
- **Characteristic stress at 1% total strain** $f_{p(1)k}$ = 1670 MPa;
- **Stress at service level** σ_{sp} = 1670 MPa;

As concerns to the *pre-dimensioning phase*, the cables are full-locked coils, available at the Teci company. Section and perspective are shown on Fig. 6.3. Pre-dimensioning of the cable computes predictable max effort N^{max} in the cable, taking into account the normal effort N_{cable} is equal to 161 kN calculated in section 5.3.3 for equivalent loads at SLS. It is multiplied by the partial safety factors γ equal to 1.5 for variable actions at ULS:

$$N^{max} = \gamma \cdot N_{cable} = 161\,kN \cdot 1.5 = 241.5\,kN \tag{6.1}$$

Considering a safety coefficient of 5 on the given minimal breaking force N_{cr} is 1285 kN, most suitable cable[(2)] has a diameter ϕ equal to 36 mm and a metallic cross-section A_s to 862 mm^2:

$$N^{max} = 241.5\,kN < \frac{N_{cr}}{5} = 257\,kN \tag{6.2}$$

Ø Rope	Metallic cross section	Mass of rope per 100 m	Min breaking force	
mm	mm2	kg	daN	kgf
32	681	560	101500	103470
36	862	710	128500	130990
40	1077	890	160500	163610
44	1303	1070	194500	198270
48	1551	1280	231500	235990
58	1841	1520	275000	280330
56	2136	1760	319000	325180
60	2452	2020	366000	373090
64	2789	2300	416500	424570
68	3149	2600	470000	479110
72	3530	2910	521000	531100
76	3933	3240	579000	590220
80	4358	3590	640500	652910
84	4805	3960	704500	718150
88	5274	4350	772000	786960
92	5764	4750	843000	859330
96	6276	5170	916500	934260
100	6890	5680	1005000	1024470
104	7452	6140	1086000	1107040
108	8037	6620	1170000	1192670
112	8643	7120	1257500	1281860
116	9271	7640	1348000	1374110
120	9922	8180	1441500	1469420
124	10594	8730	1538500	1568300
128	11289	9300	1638500	1670240

Figure 6.2: Different cables supplied by Teci, from their brochure.

6.1.4 Ordinary steel for reinforcement

Ordinary steel has the following characteristics (UNI, 1992):

(2) The brochure is given in Fig. 6.2.

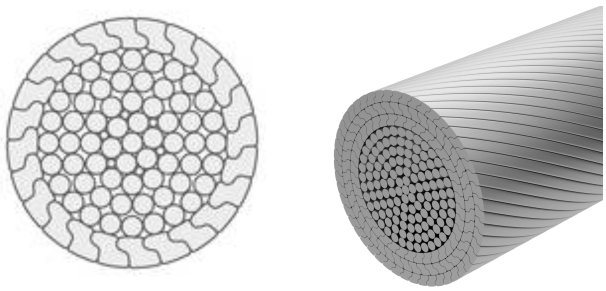


Figure 6.3: Cable, from brochure Teci.

- **Young modulus** $E_s = 200$ GPa;
- **Specific Weight** $\rho_s t = 7.85$ t/m^3;
- **Partial safety factors for steel** $\gamma_s = 1.15$;
- **Characteristic yield strength of reinforcement** $f_{yk} = 450$ MPa;
- **Design yield strength of reinforcement** $f_{yd} = 391$ MPa.

Reinforcement is constituted by welded wire meshes, calendered to give them a cylindrical shape with the correct diameter. A correct overlapping will be ensured as for classical reinforcement nets.

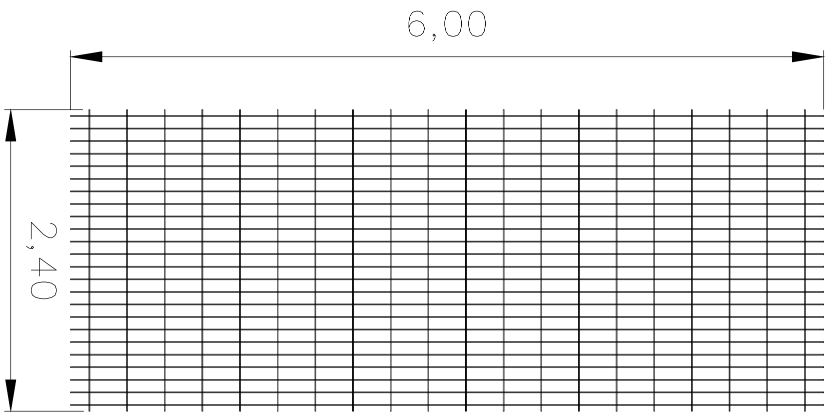


Figure 6.4: A 6 m x 2.4 m panel of welded wire, with respective spacing 0.3 m x 0.1 m.

Calendering typically result from processing the mesh between three cylinders, whose diameter is slightly smaller than nominal diameter of the tubes (250 mm). Panels have dimensions 6.00 m x 2.40 m and weight 58 kg, resulting in 4 kg/m^2 of mesh. Minimum "recouvrement" of $l_0 = 250$ mm is required by Eurocode 2 (UNI, 1992). The interior diameter of a tube is $D_i = 237.6$ mm, giving for perimeter $P_i = \Pi D_i = 746$ mm. Total length l_{panel} is therefore:

$$l_{panel} = l_0 + P_i \approx 1m \tag{6.3}$$

Linear weight of cylindrical panels g_{reinf} becomes:

$$g_{reinf} = 4\,kg/m^2 \cdot 1\,m = 4\,kg/ml \quad (6.4)$$

A typical panel is presented on Fig. 6.4. An overlapping length $l_0 \geq 250$ mm gives the shape shown on Fig. 6.5.

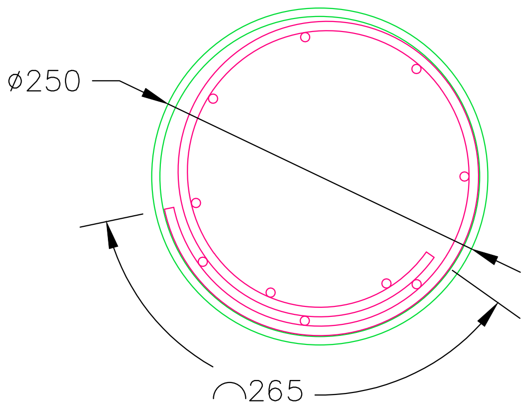


Figure 6.5: Sectional view of a reinforced concrete beam: PVC tubes are in green, reinforcing mesh is in rose, the void is filled by concrete. Overlapping exceeds 250 mm.

6.1.5 Wooden planking

Planking is made of a classical solid wood taken in service class 3 (external applications). Typical wood will be a *D35 hardwood*. Its characteristics are (UNI, 2009):

- **Average axial modulus** $E_{0,mean} = 10$ GPa;
- **Axial modulus at the 5th percentile** $E_{0.05} = 8.7$ GPa;
- **Flexural stress** $f_{m,k} = 35$ MPa;
- **Shear stress stress** $f_{v,k} = 3.4$ MPa;
- **Mean specific weight** $\rho_w^{mean} = 560$ kg/m^3;
- **Characteristic specific weight** $\rho_w^k = 670$ kg/m^3

Geometry of the planks is:

(a) Thickness $h_w = 0.1$ m $= 10$ cm;

(b) Length: 1.875 m;

(c) Width of a plank:

1. $b_w = 0.35$ m at both sides of the deck, to support the traffic load transmitted by the wheels;
2. $b_w = 0.18$ m in the central part of the deck,

(d) Weight of a plank: g = 44 kg for the widest planks, g = 22.6 kg else: they are manual handling.

At both edges of the deck, the 35 cm wide planks are associated together by mortise and tenon at midspan, to limit deflection. Technical details are given on Fig. 6.6, Fig. 6.7 and Fig. 6.8.

Figure 6.6: Wooden planking: the largest planks are on each sides, joined at their midspan by mortise and tenon.

6.2 Loads

The designed bridge is pedestrian. Therefore, traffic loads from EC2 for classical road bridges are too requiring. The normative framework is section 5 of Eurocode 1, 1991-1-2: pedestrian bridges (Eurocode, 1991). An additional exceptional traffic load is taken in account, and the most unfavourable of the two loads has to be checked.

6.2.1 Permanent loads

Permanent loads are itemised in the following, with associated typical values.

- Self-weight of PVC pipes: linear weight is expressed as g_{pvc}:

$$g_{pvc} = \gamma_{pvc}\, \pi\, e(D - e) = 7.1\, kg/ml \tag{6.5}$$

- Self-weight of cylindrical reinforcing meshes: linear weight is expressed as g_{reinf}, recalled in section 6.1.4:

$$g_{reinf} = 4\, kg/ml \tag{6.6}$$

- Self-weight of cables: linear weight is expressed as g_{cab} and given in section 6.1.3

$$g_{cab} = 7.1\, kg/ml \tag{6.7}$$

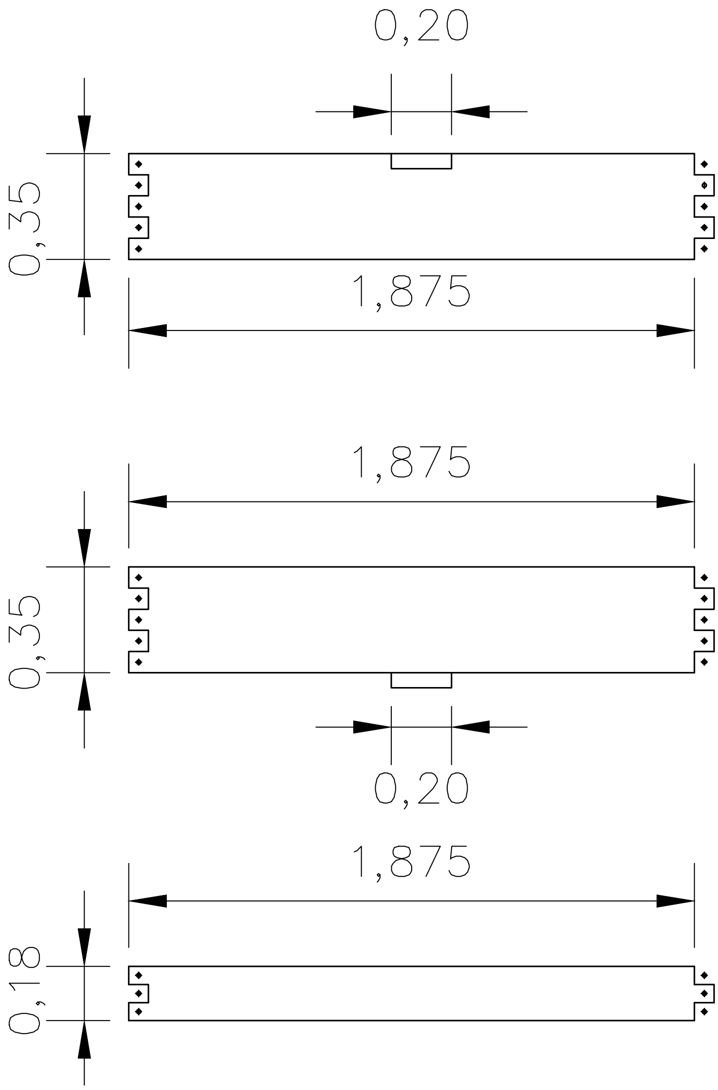


Figure 6.7: Dimensions of the planks used.

- Self-weight of concrete from the concreting phase: linear weight is expressed as g_c, including the reinforcement:

$$g_c = \gamma_c \, \pi \, \frac{(D-2e)^2}{4} = 111 \, kg/ml \tag{6.8}$$

- Self-weight of planking: linear weight is expressed as g_w, with $h_w = 0.1 \, m$ being the thickness of the planking and w = 2.2 m its width. It is a permanent non-structural load, whereas other loads are permanent structural.

$$g_w = \gamma_w \, h_w \, w_w = 147.4 \, kg/m \tag{6.9}$$

These loads are directly calculated by the FE software called Karamba (see the next Chapter), on the basis of their dimensions and specific weights, as defined in section 6.1.

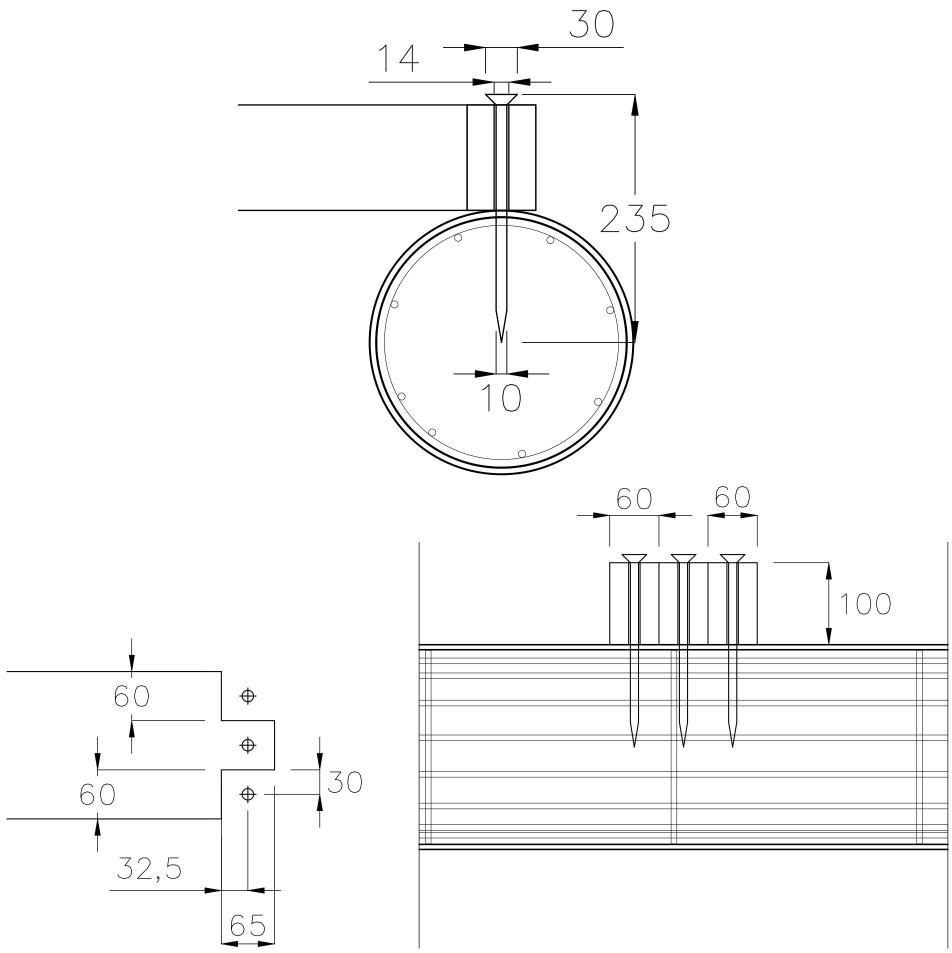


Figure 6.8: Details of assembling on the crosspieces: screws are used to provide vertical compatibility.

6.2.2 Pedestrian load

For pedestrian bridges, Eurocode 1 (Eurocode, 1991) prescribes the uniform pedestrian load $q_{fk} = 500$ kg/m^2 to be applied on the whole surface of the deck. This load is applied to the planking, and the planking bears on the crosspieces. Therefore, a linear load is transmitted to the crosspieces q_{fk}^{cp}, function of the distance between the crosspieces[3]. Except for the end crosspieces, whose load is halved, linear variable loading is:

$$q_{fk}^{cp} = q_{fk} \frac{L}{8} = 937.5 \, kg/ml \tag{6.10}$$

6.2.3 Traffic load

In case, a car would cross the bridge, for exceptional reason, the following models have been considered:

[3]There are 9 crosspieces, parting the deck in 8 segments: therefore this distance is L/8

- "Pick-up" Nissan Navara;

- Van Nissan.

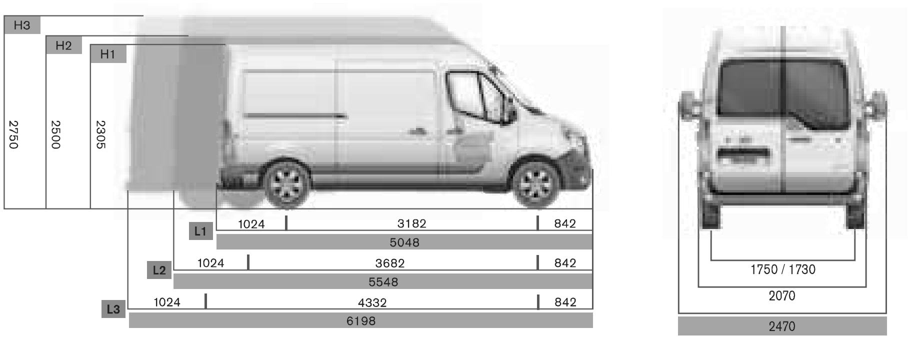


Figure 6.9: Van Nissan.

Figure 6.10: "Pick-up" Nissan Navara.

They are shown on Fig. 6.9 and Fig. 6.10. The associated technical documentation gives detail on weights and dimensions of these vehicles. They are summed up in Tab. 6.1.

(a) Wheelbase is the distance between front axle and rear axle: the most unfavourable case corresponds to the smallest wheelbase;

(b) Front/rear track is the distance between the two wheels of an axle;

(c) Overall width is the total maximal width of the vehicle, with or without mirrors;

(d) Authorized loaded weight (PTAC) is the maximal allowed weight of the vehicle, including self-weight and additional service loads.

Hence, a 2.2 m-wide bridge prevents vehicles with excessive width (and weight) to access the bridge: it allows 4 x 4 and vans, typically used on building sites.

Characteristics		**Van**	**Navara**
PTAC	[t]	3.9/5	3
Wheelbase	[m]	3.18	3.15
Front track	[m]	1.73	1.55
Rear track	[m]	1.73	1.55
Overall width	[m]	2.47	2.08
Overall width without mirrors	[m]	2.07	1.85

Table 6.1: Main characteristics of weight and dimensions of the vehicles considered.

Most unfavourable loading resultant from Tab. 6.1 is constituted by a 5 t van with 3.15 m wheelbase. Critical moment is given by Asimont's theorem: for a couple of force $2Q$, whose spacing is r (the rear), maximum moment along a supporting beam of width w [m] is in the central section, if and only if:

$$\begin{aligned} \frac{w}{2} &< \frac{3}{4} r \\ r &> \frac{2}{3} w \end{aligned} \tag{6.11}$$

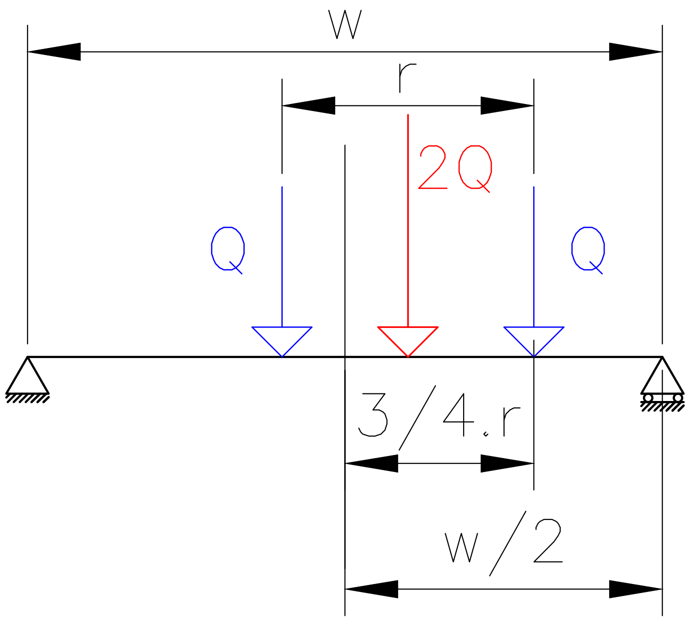


Figure 6.11: Illustration of the implicit condition of Asimont's theorema.

In the present case Asimont's problem has no solution. Worst case scenario is then the following symmetrical loading, as on Fig. 6.12.

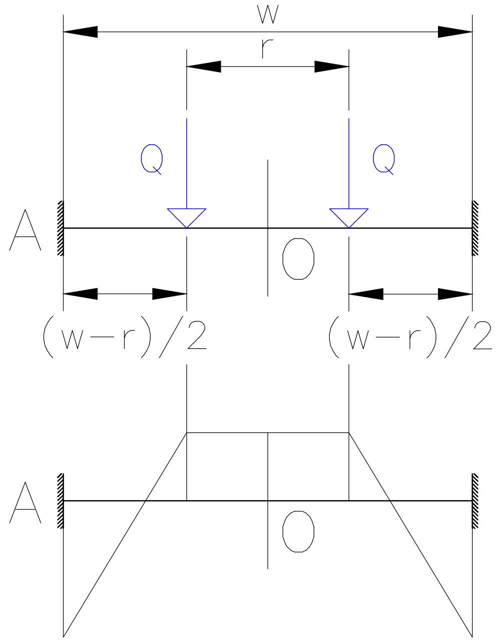


Figure 6.12: Flexion of a crosspieces under an axle.

With the hypothesis of a clamped beam, and for Q = 1.5 t[4]:

- vertical reactions on the supports are Q at each end;

- maximal moments at the end M_A and at midspan M_0 are:

$$M_A^{max} = -\frac{Q\,(w+r)(w-r)}{4\,w} \qquad M_0^{max} = \frac{Q\,(w-r)^2}{4\,w}$$
$$M_A^{max} = -\frac{1.5\,(2.2^2 - 1.55^2)}{4 \cdot 2.2} = -415\,kg.m \qquad M_0^{max} = \frac{1.5\,(2.2-1.55)^2}{4 \cdot 2.2} = 72\,kg.m \tag{6.12}$$

$$M_0^{max} = \frac{Q\,(w-r)^2}{4\,w}$$
$$M_0^{max} = \frac{1.5\,(2.2-1.55)^2}{4 \cdot 2.2} = 72\,kg.m \tag{6.13}$$

As a consequence, input efforts for Karamba to model the traffic loads are the end moments M_A and vertical reactions Q.

[4] It is a conservative value for the load by wheel, given that it takes the fourth of the PTAC and it raises it by 20% to take into account asymmetrical effects.

6.3 Supports

Specific supports are designed for the project. Indeed, designer is confronted to two incompatible problems:

- on the one hand, the statical scheme leans on the hypothesis that the bridge is simply supported: no clamping must be provided at the supports and longitudinal translation should be released at one end;

- one the other hand, PVC fittings can absolutely not resist the massive normal force acting in the cable at the end of Phase 3, when concrete has not dried yet (see section 6.4).

Therefore, solution implements a concrete block with special disposition to respect the statical scheme. First, both PVC elbows are cut to prepare space for a metallic cylinder to pass through. Then, metallic tube and PVC elbows are sealed in a concrete block and set up on a elastomer support that provides rotation and longitudinal translation abilities. A threaded rod ($\phi 40mm$), passing through the metallic tube, is joined to the cable at on end, and tightened against the supports with appropriate clamping nuts ($\phi 100mm$). Fig. 6.13, Fig. 6.14 and Fig. 6.15 illustrates the implementation of the supports.

Figure 6.13: Section view of the concrete supports: from behind at the left, from the deck at the right.

6.4 Phases

This part will detail for each phases the associated loads, resisting materials, hypothesis, construction actions and necessary verifications.

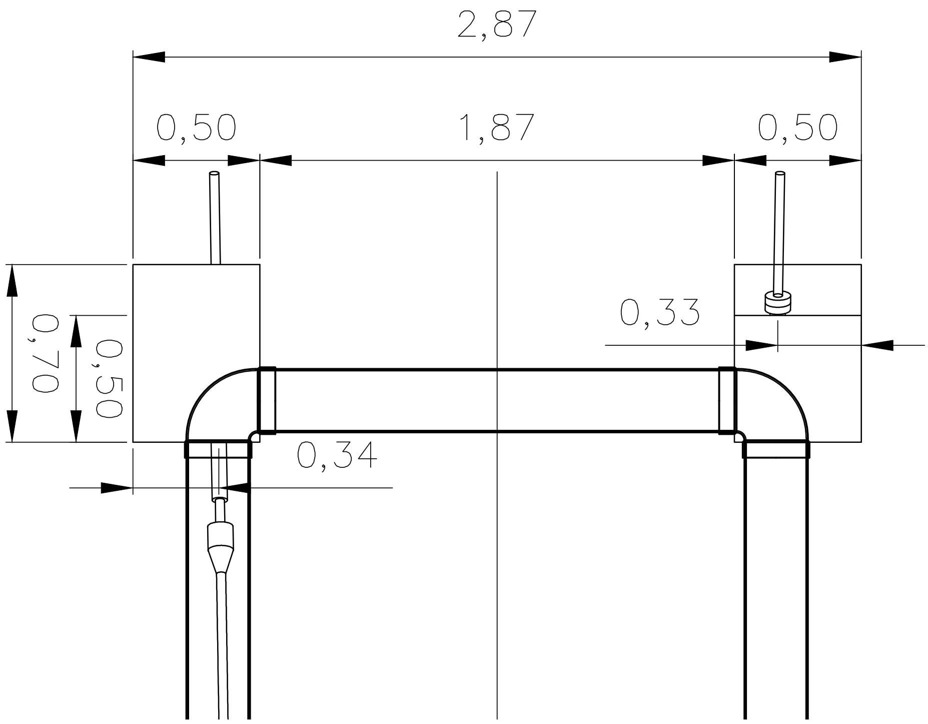


Figure 6.14: Top (on the right) and bottom (on the left) views of the supports.

6.4.1 Preliminary Phase

Calendered reinforcement meshes are disposed in every tubes. They are fixed to the tubes by appropriate screws at tubes ends to prevent reinforcement to disengage from the plastic tubes. Their length l_s shall exceed the thickness of the tubes e, and the thickness of the welded wire mesh e_{reinf}:

$$l_s \geq e + e_{reinf} > 6.2\,mm + 2 \cdot 7\,mm \approx 21\,mm \tag{6.14}$$

The length of the mesh exceeds the length of the tube by l_+ at each end to provide overlapping in the fittings and ensure clamping of the joints. For the overlapping lengths, circumferential steel rings are removed to make interlacing with other meshes and with bearing cable possible. Given the geometry of the elbows, a good value for l_+ is:

- $\approx$ 20-25 cm for the lower end of columns, for and for both ends of crosspieces;
- $\approx$ 55 cm for the upper end of columns;
- $\approx$ 25 cm for the deck members.

Fig. reffig:reinf shows typical disposition of reinforcing cylinders the plastic tubes. Circumferential bars are removed near both ends to help the bars writh near the fittings.

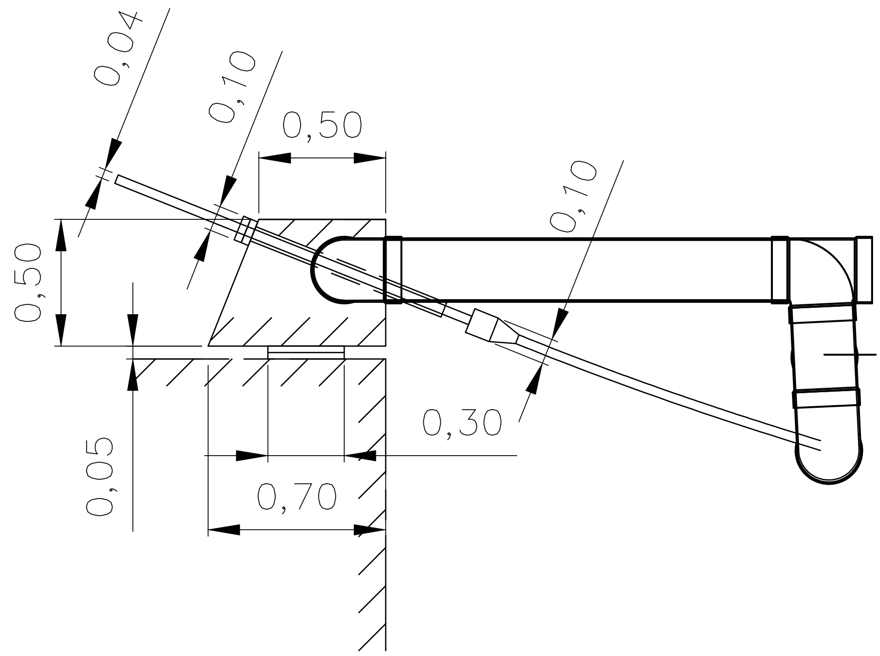


Figure 6.15: Lateral view of the supports: the footbridge lies on special hooped bearings, entirely coated with elastomer.

Then intermediary supports are installed. Their position coincides with midspan of each deck element. End supports are realized, in accordance with section 6.3.

Finally, circular holes are made in fittings, so as to let the cable pass through. Holes will have a diameter d_{hole} slightly greater than the diameter of the cable ϕ_{cable}:

$$d_{hole} \geq \phi_{cable} \tag{6.15}$$

For ϕ_{cable} equal to $36\,mm$, d_{hole} equal to 40 mm is convenient.

At this stage, all members are ready to be assembled.

6.4.2 First Phase

During the first construction phase, the PVC skeleton is constructed:

- PVC elbows in which passes the cable are threaded along the cable;
- Cables are installed at the end supports: they are threaded into cylindrical metallic tubes and temporarily blocked at proper length.
- PVC tubes and fittings are assembled by means of solvent cementing: as recalled in section 4.3, such joints are at least as strong as the pipe of the fitting. They will ensured sealing during concreting phase. For each transversal framework, procedure will respect the following order:

1. inferior crosspieces and columns are assembled to the elbows that are threaded along the cable. Cable provides resistance;
2. superior crosspieces are connected to tees and to columns;
3. deck elements are assembled horizontal tee and connected to the transversal structures.

Transversal framework are built starting from midspan and then symmetrically.

The length of the cable is adapted to compensate for the shape of the footbridge. The loads acting in this Phase are self-weight of PVC, cable and reinforcement nets.

6.4.3 Second Phase

The wooden planking is added. It is fixed to superior crosspieces by means of long screws, so as to be sealed in the concrete to pour in the third phase. A special shape is given to be able to associate 2 wooden beams at the same point of a cylinder, as Fig. 6.7 and Fig. 6.8 describe.
Every hole is inspected and voids are sealed with plastic joints to avoid concrete leaks.
At the end of the second phase, the length of the cable is adjusted to give to the structure the most straight shape possible before concreting phase.
The given loads are:

- Self-weight of PVC, cable and reinforcement nets;
- Self-weight of the planking is added to the loads.

Figure 6.17: Assembling details of the wooden planking.

6.4.4 Third Phase

Third phase corresponds to concreting: self-compacting concrete is poured in holes dug in the upper part of the deck elements, at midspan. In this way, concrete fills horizontal members and flows in the columns. Such a procedure has been used in the for the concrete bridge of chapter 1.
The length of the cable is adjusted.
The given loads are:

- Self-weight of PVC, cable and reinforcement nets;
- Self-weight of the planking;
- Self-weight of concrete freshly poured.

Some checks need to be performed:

- SLE: resistance of the plastic tubes to the loads;
- SLE: deflection of tubes is admissible and negligible so as not to alter the shape of concrete structure.

These checks verify automatically the first and second phases.

6.4.5 Fourth Phase

During the fourth phase, the cable is tightened and blocked so as to lift the bridge away from the intermediary supports. Hence, these supports are removed. An order of magnitude of the necessary shortening of the cable is ΔL, based on the model calculation and on the length of the parabolic cable:

$$\Delta L = \epsilon \cdot L \approx 0.5\% \cdot 15.3\, m \approx 7.7\, cm \tag{6.16}$$

Loads are identical to the 3rd phase.

6.4.6 Fifth phase

Computation of the bridge is made under the variable loads, as described in section 6.2. Two computations are necessary the criticality of a load may depend on the computed member.
As concerns the loads, it has:

- Self-weight of PVC, cable and reinforcement nets;
- Self-weight of the planking;
- Self-weight of concrete freshly poured;
- Traffic load or pedestrian load.

At SLE and SLU, it is important to check:

- SLU: resistance of the reinforced concrete sections to the loads: bending/shear in longitudinal members, and transversal members;
- SLE: deflection of the structure under imposed load;
- SLU: resistance of the cable;
- SLU: stability of the structure (resp. members) against global (resp. local) buckling ;
- SLE: limitation of stress in members;
- SLE: deflection of the structure under imposed load;
- SLE: cracking of members
- SLE: deflection of the structure under imposed loads and deflection of members;
- SLU & SLE: wooden planking under variable loads.

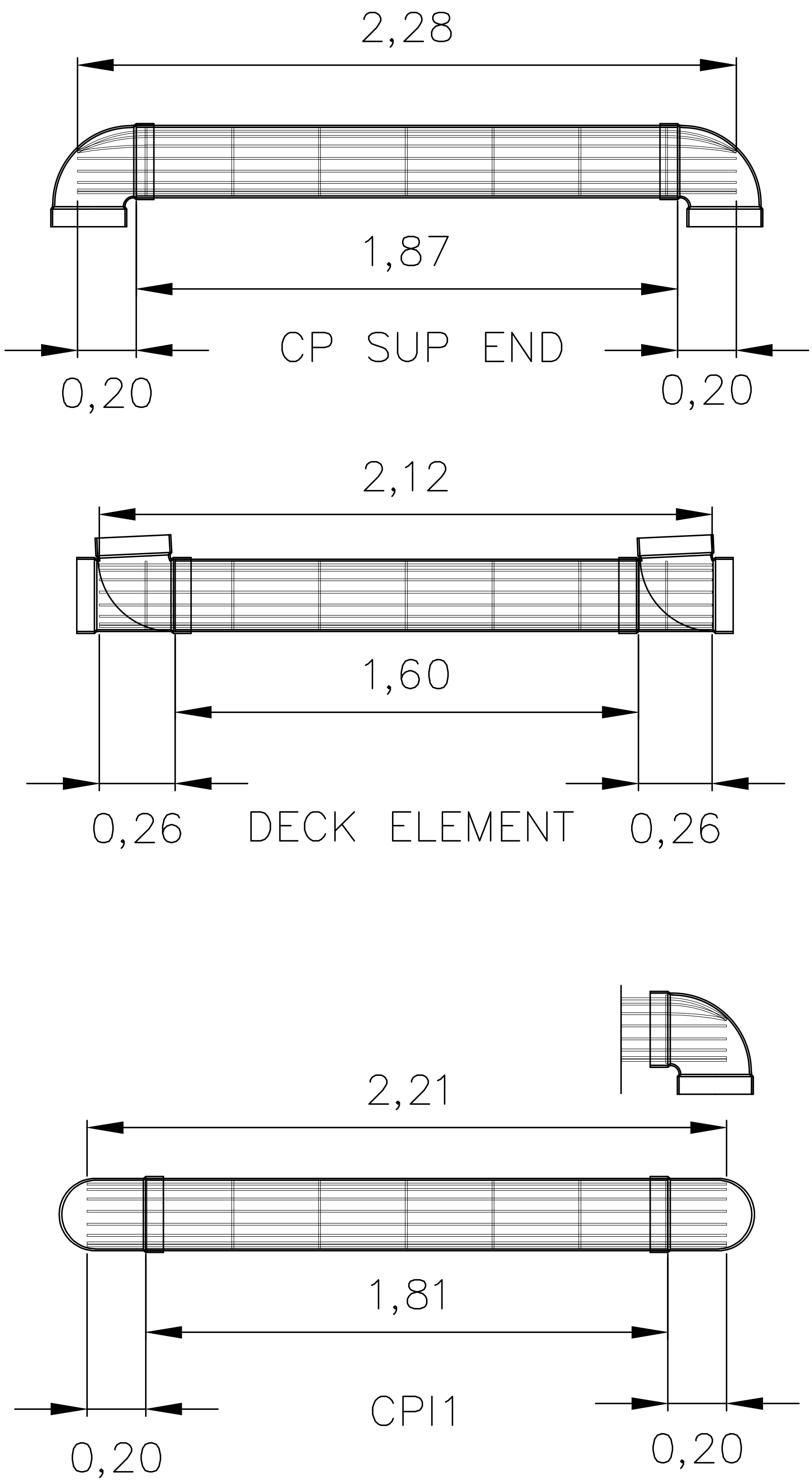


Figure 6.16: Dimensions of reinforcing cylinders and tubes for some elements: end crosspieces, deck, and inferior crosspieces (CPI) of section 1-1.

Chapter 7

Structural Analysis

This chapter presents the principle of the finite elements (FEM) modeling of the footbridge. It describes the structural verifications made of the different elements at the different steps of the construction.

7.1 Algorithm and its implementation

This section will briefly introduce the different softwares used for the present work and also reported in Attachment A. For more detailed information, the reader is invited to consult the visual tutorials and articles explaining extensively their functions.

7.1.1 Rhino3D

Rhinoceros or Rhino3D is hence used in CAD (Computer-Aided Design) or CAM (Computer-Aided Manufacturing) processes:

- rapid prototyping;
- 3D printing;
- architecture;
- industrial design;
- product design (jewelry);
- multimedia and graphic design.

It also has a parametric modelling tool add-on: Grasshopper.

7.1.2 Grasshopper

Grasshopper is a visual programming language that runs within Rhino3D. It is primarily used to build generative algorithms. Many of its components create 3D

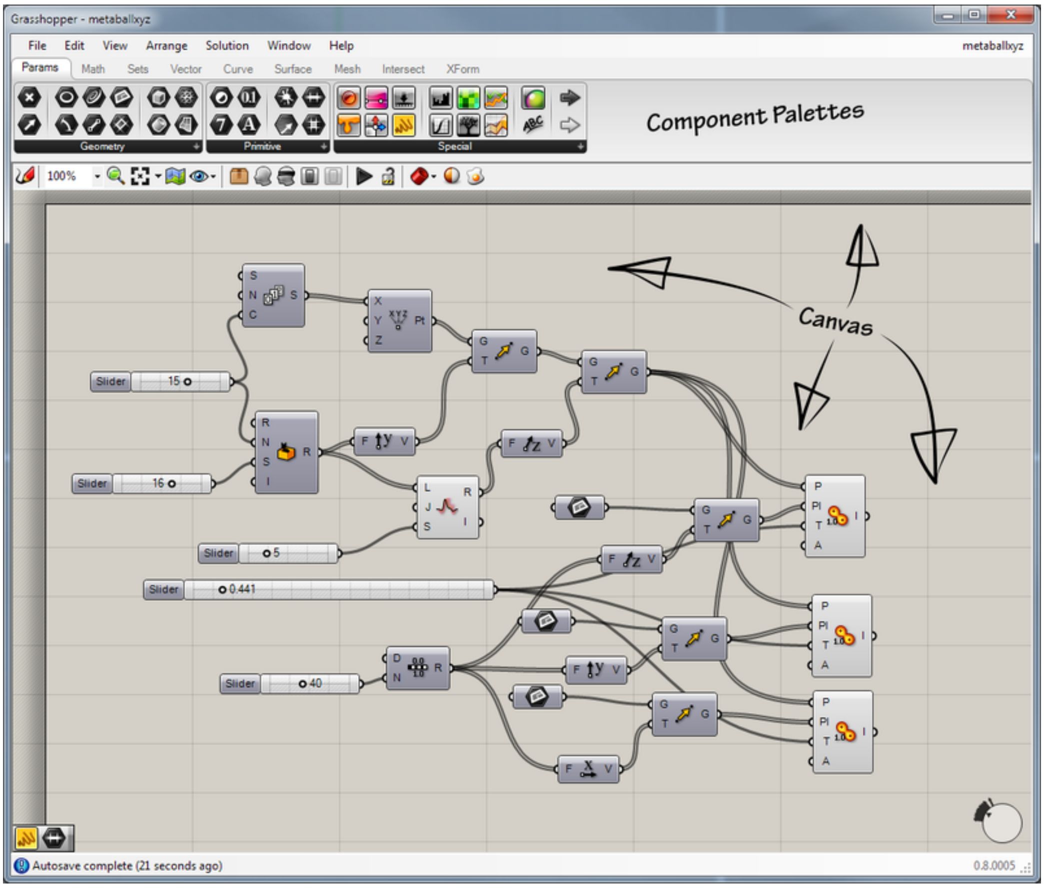


Figure 7.1: A Grasshopper window.

geometry directly printed in Rhino space. Programs also include numeric, textual or audio-visual applications.
The main interface for algorithm design in Grasshopper is the node-based editor. As shown on Fig. 7.1, programs are created by dragging components onto a canvas. Information is passed from component to component via connecting wires which always connect an output grip with an input grip. Data can either be defined locally as a constant, or it can be imported from the Rhino document or a file on the computer. It is always stored in parameters, which can either be free-floating or attached to a component as input and outputs objects. Grasshopper structures information in trees, to deal efficiently with potentially high numbers of parameters. Its principle makes it a very intuitive way to explore designs. A simple change of parameter automatically modifies the impacted data. Combined to the FEM software Karamba, it allows for direct FE computation and printing of the results – efforts, stresses, displacements – in the Rhino screen. Therefore, in the *scope of this work*, its use was extremely handy to help determine:

1. the appropriate shape of the footbridge;
2. its correct parameters: height, number of columns, angles, etc.

7.1.3 Karamba

Karamba3D is an interactive and parametric FE program. It provides accurate analysis of 3-D beam, truss or shell structures under arbitrary loads.
It is fully embedded in the parametric environment of Grasshopper. This makes it easy to combine parametrized geometric models, finite element calculations and optimization algorithms. It is mostly used for optimization and conception, as it allows to directly observe the result of parameter variations on the structural behaviour of the structure.
Examples of combined usage of Karamba, Grasshopper and Rhino are showed in section 7.3. A logical flow charts in section 7.1.4 details the articulation and interoperation of Rhino3D, Grasshopper and Karamba3D.

7.1.4 Flowchart

Logical process for parametric design follows the steps described in Fig. 7.8. Any modification of a parameter causes an automatic update of the depending components: as the elements are defined with respect to each other, the modification of a parameter reverberate on the entire chain.

1. **Choice of the parameters**;
these parameters have to describe comprehensively the problem: because they are the keystone of the process. Obviously, to ensure efficiency of the design, final parameters have to be as few as possible.
For an example: L (length), H (height), w (width);

2. **Construction of the parametric geometric model** on Grasshopper;
the geometry consists of lines, points, splines, organized in trees and lists. Elements are built on the basis of existing geometry at the previous steps:

   (a) Shape of the deck and parabolic cables, based on parameters L, H, w;

   (b) Columns, from parameters N_x (number of columns) and from step 1;

   (c) Crosspieces, connect both ends of columns, based on step 3;

3. **Conversion of the geometry into a FE model** thanks to Karamba, in the Grasshopper environment:

   (a) Elements (beams), and proper IDs and sets;

   (b) Cross-sections;

   (c) Materials;

   (d) Supports;

   (e) Joints between the elements;

   (f) Loads;

   (g) Computation algorithms;

4. **Structural optimisation**, with inter-connection between parameter changes and structural results. Parameters can be changed, improved and reduced during the construction of the geometry and of the FE model.

5. **Post-processing of the result**, visualization on the Rhino 3D model and export of data (for example to Excel).

7.2 Combinations

In the following, G, Q, q, and PS respectively represents the permanent – structural and non-structural – loads, the traffic actions, pedestrian load, and intensity of prestressing.

Tab. 7.1 shows the different combinations that have been computed to check limit states: ULS & SLS (Ultimate Limit State and Serviceability Limit State respectively).

Loading Case	G	Q	q	PS	Limit State
LC0	1.0	0.0	0.0	1.0	T_0
LC1	1.35	1.5	0.0	1.0	ULS
LC2	1.35	0.0	1.5	1.0	ULS
LC3	1.0	1.0	0.0	1.0	SLS
LC4	1.0	0.0	1.0	1.0	SLS
LC5	1.0	0.0	0.0	1.35	ULS
LC6	1.0	1.5	0.0	1.0	ULS
LC7	1.0	0.0	1.5	1.0	ULS

Table 7.1: Coefficients applied to the loads according to the nature of the limit state and the type of loading.

7.3 Computation on Karamba

Computation are made according to FE principles on Karamba: generalized efforts N, M, V are computed and diagrams can be plot directly on the structure. Interoperability of Grasshopper and Rhino can be shown on Fig. 7.2.

7.3.1 Traffic impact modelling

Figu. 7.3 shows the way a traffic load is implemented in Rhino. Torsional actions creates flexural moments in the crosspieces and in the columns, similarly to the pedestrian load on Fig. 7.2. Flexion in the inferior crosspieces is very limited.

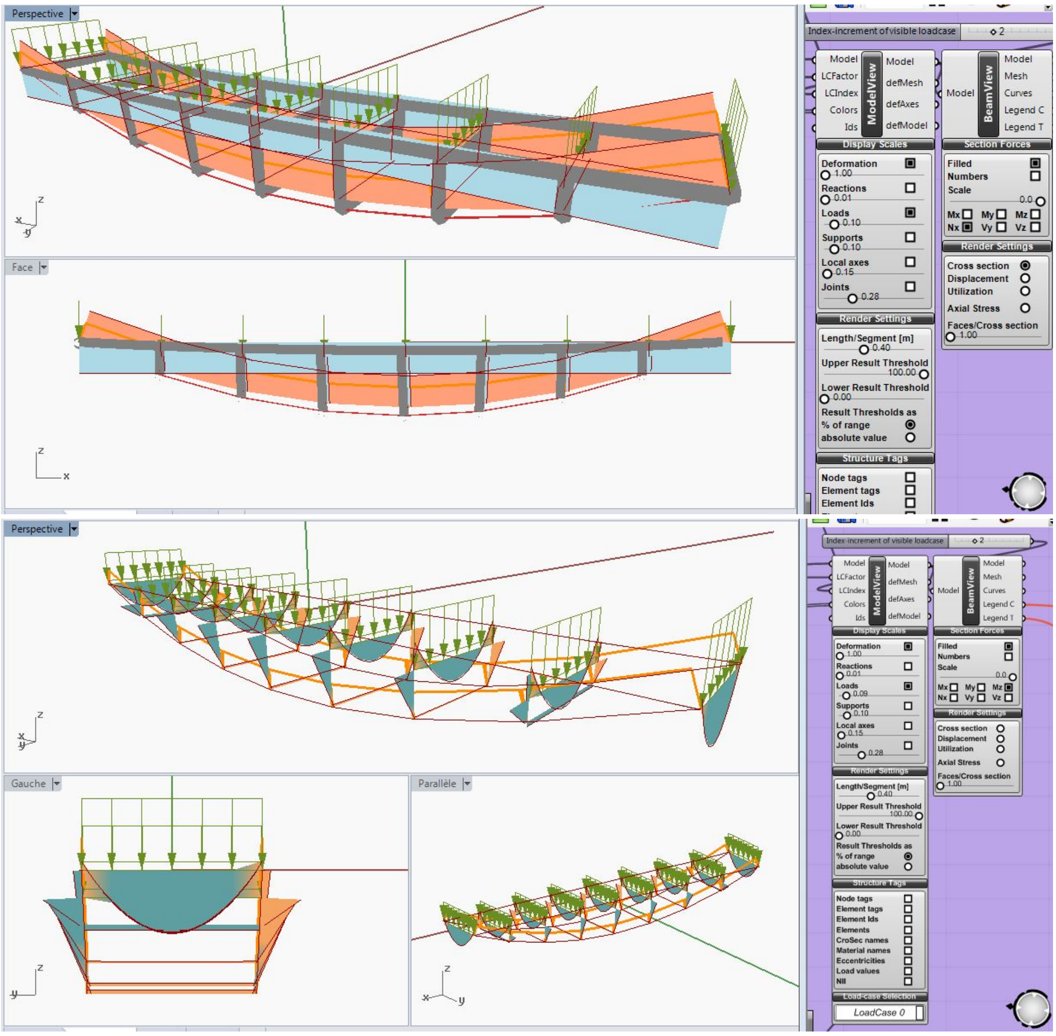


Figure 7.2: Interoperability of Grasshopper and Rhino: Grasshopper components controls the graphical schemes in the Rhino screen.

7.3.2 Actions in the concrete elements

Generalized actions and sectional stresses are detailed in Tab. 7.2 and in Tab. 7.5: N, M, V, σ_{min}, σ_{max}, computed for every section by Karamba as:

$$\begin{aligned} \sigma_{min} &= \frac{N}{A} - \frac{M}{I}\frac{D}{2} \\ \sigma_{max} &= \frac{N}{A} + \frac{M}{I}\frac{D}{2} \end{aligned} \tag{7.1}$$

N is the tensile or compressive normal force on a section, M and V are the total moment and shear forces acting on a section, summed up for all normal directions (including M_y and M_z, V_y and V_z).

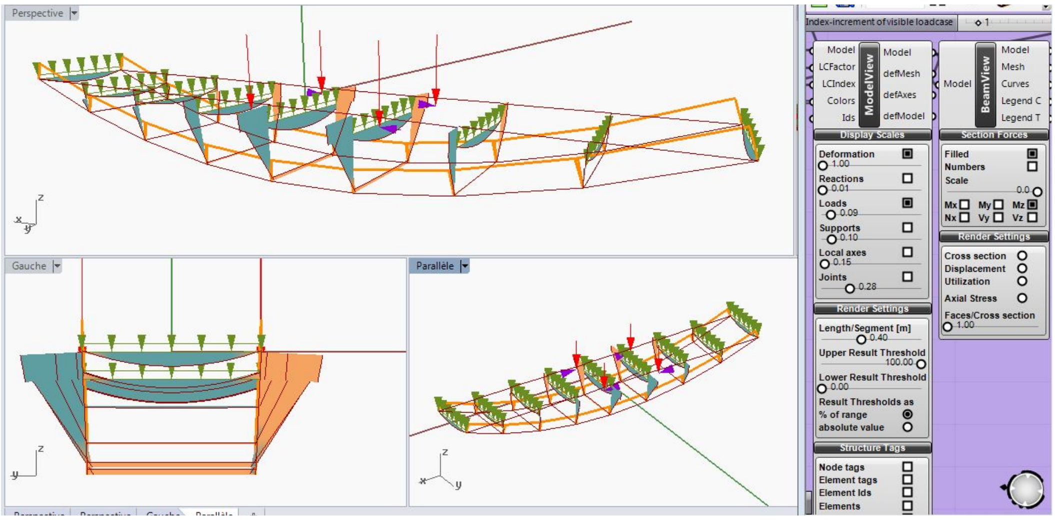


Figure 7.3: Model of a car load: 4 vertical forces localized at the deck, and 4 torsional moments to account for the eccentricities of the wheels with respect to the edges of the deck.

Loading Case	$\boldsymbol{N}$ [kN]	$\boldsymbol{M}$ [kNm]	$\boldsymbol{V}$ [kN]	σ_{min} [MPa]	σ_{max} [MPa]
LC1	-25.3	17.2	30.3	-15.2	11.2
LC2	-175.2	2.1	10.9	-5.5	-2.4
LC3	-18.8	11.4	18.4	-10.2	7.4
LC4	-119.9	1.3	4.7	-3.6	-1.7
LC5	-18.9	2.1	2.1	-2.1	1.1
LC6	-18.8	17.2	29.6	-15.1	11.4

Table 7.2: Maximum actions in sections and extremal linear stresses, calculated along the deck.

Loading Case	**N** [kN]	**M** [kNm]	**V** [kN]	σ_{min} [MPa]	σ_{max} [MPa]
LC1	1.7	0.5	0.1	-0.6	0.2
LC2	14.3	0.8	0.1	-0.3	0.9
LC3	1.2	0.3	0.1	-0.4	0.2
LC4	9.7	0.5	0.1	-0.2	-0.6

Table 7.3: Maximum actions in sections and extremal linear stresses, calculated along the inferior crosspieces.

Reminding that a C25/30 has a design compression value of f_{cd} equal to 14.16 MPa and a tensile capacity of f_{ctm} equal to 2.1 MPa, actions and stresses in the sections are presented in the Tab. 7.2, Tab. 7.3, Tab. 7.4 and Tab. 7.5, for the different elements under their most critical load cases:

- deck elements, under LC1 to LC6;

- crosspieces, under LC1 to LC4;

- columns, under LC1 to LC6;

Loading Case	**N** [kN]	**M**[kNm]	**V** [kN]	σ_{min} [MPa]	σ_{max} [MPa]
LC1	8.5	5.3	2.0	-4.0	4.0
LC2	0.0	8.3	17.4	-6.3	6.3
LC3	5.6	3.5	1.5	-2.7	2.7
LC4	0.0	5.6	11.8	-4.3	4.3

Table 7.4: Maximum actions in sections and extremal linear stresses, calculated along the superior crosspieces.

Loading Case	**N** [kN]	**M** [kNm]	**V** [kN]	σ_{min} [MPa]	σ_{max} [MPa]
LC1	-0.2	21.4	20.0	-16.4	16.0
LC2	0.6	5.5	14.4	-4.6	3.8
LC3	-0.1	14.3	13.3	-11.0	10.7
LC4	0.3	3.7	9.8	-3.1	2.6
LC5	-0.2	1.5	2.5	-1.2	1.1
LC6	-0.1	21.4	19.7	-16.4	16.0

Table 7.5: Maximum actions in sections and extremal linear stresses, calculated along the columns.

7.3.3 Actions in the cables

The computed forces in each cable are shown in Tab. 7.6.

Loading Case	***N*** [kN]
LC1	29.7
LC2	185.7
LC3	22.0
LC4	126.0
LC5	23.2
LC6	22.0

Table 7.6: Maximum actions in sections and extremal linear stresses, calculated along the columns.

7.4 Global behaviour of the structure

7.4.1 Instability (ULS)

Karamba includes a second order analysis algorithm. It allows to compute global and local buckling buckling modes and coefficients. Calculation has been led for LC1 and LC2, at ULS, as they are those giving most elevated compression in the structure.
Initial time t_0 is defined as the time for which concrete has hardened and for which the structure is not loaded yet. The structure is given a positive camber because the cable is pre-stressed. As it has a substantial self-weight, the deck is bent and compressed. Buckling must be studied to ensure safety.
Worst-case computed buckling coefficient is:

$$f_{buck} = 7.2$$

This value is acceptable.

7.4.2 Deflection (SLS)

Deflections at midspan of the structure are calculated at SLS, with maximal variable loads (negative deflection, under LC3 and LC4) and without variable load (positive camber, under LC5). Results are compared to the overall length L equal to 15 m.

Loading Case	**Deflection** [cm]	**Criteria**
LC3	11	L/120
LC4	-9.5	L/150
LC5	11	L/120

Table 7.7: Deflection of the structure.

Deflection are quite elevated. Two reasons can be found:

- the two bearing cables are too thin, or one should add a third cable, at midspan of each crosspiece, because deflection is controlled by the cable, not by the rigidity of the concrete structure;

- the structure leans on a simply supported statical scheme. Clamping the supports would cancel compression in the deck a generate too many efforts at the supports.

7.5 Plastic tubes

The loading of plastic tubes is only transitory. Therefore, only SLS are checked, at the end of step 3. They mainly consist of the verification of:

- resistance of the section: it regards both axial resistance of the tubes to normal forces before hardening of concrete (worst case occur in the deck) and bending resistance of superior crosspieces;

- limited deflection so as to consider straight concrete tubes.

7.5.1 Deflection

Worst case deflection is the bending of crosspieces, which are conservatively considered as simply supported (bending resistance of the fittings is neglected). Because traffic loads Q are applied near the supports, maximal deflection (at midspan) is computed as:

$$v_{L/2,q} = \frac{q\, l_{cp}^4}{384\, EI} \tag{7.2}$$

Where:

- q [kN/ml] is the uniform distributed load, consists of the planking, reinforced concrete and plastic linear weights:

$$q = g_w + g_c + g_p = 125 + 111 + 7 = 243 kg/ml \tag{7.3}$$

  where the linear weight of wooden planking is computed as:

$$g_w = \gamma_w \cdot h_w \cdot l = 670\, kg/m^3 \cdot 0.1\, m \cdot 1.875\, m = 125\, kg/ml \tag{7.4}$$

- l_{cp} = 2.2 m is the length of a crosspiece;

- E = 2900 MPa is the Young modulus of PVC;

- I = $\frac{\pi\, D^4}{64}$ - $\frac{\pi\,(D-2e)^4}{64}$ = 3.5 x10^{-5} m^4 is the moment of inertia of a plastic tube of thickness e and external diameter D.

One can obtain:

$$v_{L/2,q} = 7.3 mm \tag{7.5}$$

According to the limit provided by the Code:

$$\frac{v_{L/2,q}}{L} = 0.33\% < \frac{L}{300} \tag{7.6}$$

7.5.2 Normal resistance

Normal resistance states that the stress in PVC must remain minor than the design short-term limit resistance of PVC, which is 22 MPa.

$$\sigma_{ax} = \frac{N}{A} \tag{7.7}$$

With:

- A $= \dfrac{\pi(D^2-(D-2e)^2}{4} = 4.75$ x10^{-3} m^2;
- N = -19kN is the maximum normal action computed at t = t_0 by the FE software.

One can obtain:

$$\sigma_{ax} = \frac{-19000}{4750} = 4\,MPa < 22MPa \tag{7.8}$$

The critical Euler buckling action of a deck element is N_{cr}:

$$\begin{aligned} N_{cr} &= \frac{\pi^2\,EI}{l^2} \\ N_{cr} &= \frac{\pi^2\cdot 2.9\cdot 35}{1.875^2} = 285\,kN \end{aligned} \tag{7.9}$$

The ratio results:

$$\frac{N_{cr}}{N} = 15 \tag{7.10}$$

Safety against buckling is ensured by a factor 15.

7.5.3 Bending resistance

As for section 7.5.2, the stress in PVC shall not exceed 22 MPa. Even if the section are compressed, normal stresses are neglected. Maximal bending stress σ_b and maximal bending moment M at t = t_0 are computed as:

$$\begin{aligned} M &= \frac{q\,l_{cp}^2}{8} \\ \sigma_b &= \frac{D}{2}\frac{M}{I} \end{aligned} \tag{7.11}$$

Where:

- q = 243 kg/ml as calculated in section 7.5.1;
- l_{cp} = 2.2 m.

One can obtain:

$$\begin{aligned} M &= 1.47\,kN.m \\ \sigma_b &= 5.25\,MPa < 22\,MPa \end{aligned} \tag{7.12}$$

The PVC tubes can resist the self-weight of concrete during concreting.

7.6 Wooden Planking

The planking has to be checked in accordance to requirements of Eurocode 5. Checks have to be made under variable loading, as the planking is not loaded in other phases. Two criteria are to be respected:

- Deflection, at SLS;
- Resistance, at SLU.

7.6.1 Deflection

General formulas for the midspan deflection $v_{L/2}$ [m] of a simply supported beam are:

$$v_{L/2,q} = \frac{5\,q\,L^4}{384\,EI} \qquad v_{L/2,Q} = \frac{Q\,L^3}{48\,EI} \tag{7.13}$$

Where:

- Q [kN] is a point load, applied at midspan;
- q [kN/ml] is a uniform distributed load;
- L [m] is the length of the beam;
- E [MPa] is the Young modulus of the wood in longitudinal direction;
- I [m^4] is the moment of inertia is the section, function of the thickness of the planking h_w and of the width of a plank b_w expressed as:

$$I = \frac{b_w\,h_w^3}{12}$$

Most critical loading is traffic loading, since it would make the load of a wheel lean on a single plank. In the design situation, at service limit state, reminding that $b_w < 2.2$ m:

$$\frac{v_{L/2,q}}{v_{L/2,Q}} = \frac{q\,L}{8\,Q} = \frac{500\,b_w\,L}{8 \cdot 1500} = \frac{5\,b_w}{64} < 1 \tag{7.14}$$

In case of *35 cm wide planks under traffic load*, at SLS, deflection states:

$$w = Q\,\frac{L^3}{4\,E_{0,mean}\,b_w\,h_w^3} \tag{7.15}$$

With :

- Q = 1.5 t for the computation of instantaneous deflection w_{inst};
- Q = (1.5 t) $k_{def}\,\phi_2$ for the computation of delayed deflection w_{creep}, with:
  $\phi_2 = 0.8$ for worst case;
  $k_{def} = 2$ for outdoor application and massive wood;

The checks are:

$$w_{inst} < \frac{L}{300} \qquad w_{inst} + w_{creep} < \frac{L}{200} \tag{7.16}$$

The tenon allows to divide the load by 2 as it is carried by to identical planks linked by a tenon.

Computation:

$$\begin{aligned} w_{inst} &= \frac{Q}{2} \cdot \frac{L^3}{4\, E_{0,mean}\, b_w\, h_w^3} \\ &= \frac{0.0075MN \cdot (1.875m)^3}{4 \cdot 10000MPa \cdot 0.35m \cdot (0.1m)^3} \\ &= 3.5mm < \frac{L}{300} = 6.25mm \end{aligned} \tag{7.17}$$

$$\begin{aligned} w_{creep} &= k_{def} \cdot \phi_2 \cdot \frac{Q}{2} \cdot \frac{L^3}{4E_{0,mean}\, b_w\, h_w^3} \\ &= \frac{2 \cdot 0.8 \cdot 0.0075MN \cdot (1.875m)^3}{4 \cdot 10000MPa \cdot 0.35m \cdot (0.1m)^3} \\ &= 5.66mm \end{aligned} \tag{7.18}$$

Summing up the two terms, it has:

$$w_{inst} + w_{creep} = 9.2mm < \frac{L}{200} = 9.37mm \tag{7.19}$$

For *18 cm wide planks under pedestrian load*, at SLS, deflection states:

$$w = q \cdot \frac{5}{32} \cdot \frac{L^4}{E_{0,mean} h_w^3} \tag{7.20}$$

With :

- q = 500 kg/m^2 for the computation of instantaneous deflection w_{inst};
- q = 500 kg/m^2 $k_{def}\, \phi_2$ for the computation of delayed deflection w_{creep}, with:
  ϕ_2 = 0.8 for worst case
  k_{def} = 2 for outdoor application and massive wood;

The verifications are:

$$\begin{aligned} w_{inst} &< \frac{L}{300} \\ w_{inst} + w_{creep} &< \frac{L}{200} \end{aligned} \tag{7.21}$$

Computation:

$$\begin{aligned} w_{inst} &= q \cdot \frac{5}{32} \cdot \frac{L^4}{E_{0,mean} h_w^3} \\ &= \frac{0.005MN \cdot (1.875m)^4}{10000MPa \cdot (0.1m)^3} \\ &= 0.97mm < \frac{L}{300} = 6.25mm \end{aligned} \tag{7.22}$$

$$\begin{aligned} w_{creep} &= k_{def} \cdot \phi_2 \cdot q \cdot \frac{5}{32} \cdot \frac{L^4}{E_{0,mean} h_w^3} \\ &= \frac{2 \cdot 0.8 \cdot 0.005MN \cdot (1.875m)^4}{10000MPa \cdot (0.1m)^3} \\ &= 1.54mm \end{aligned} \tag{7.23}$$

Summing up the two terms, it has:

$$w_{inst} + w_{creep} = 2.5mm < \frac{L}{200} = 9.37mm \tag{7.24}$$

7.6.2 Flexural resistance

For resistance, dimensioning action is the midspan moment M$_{L/2}$ [kNm] created by the variable loading:

$$\begin{aligned} M_{L/2,q} &= \frac{q\,L^2}{8} \\ M_{L/2,Q} &= \frac{Q\,L}{4} \end{aligned} \tag{7.25}$$

Again, most critical situation is represented by traffic loading:

$$\frac{M_{L/2,q}}{M_{L/2,Q}} = \frac{q\,L}{2\,Q} = \frac{500 b_w L}{2 \cdot 1500} = \frac{5 b_w}{16} < 1 \tag{7.26}$$

Hence, verification is made only for 35 cm wide planks. At ULS, verification states:

$$\frac{\sigma_{m,d}}{k_{crit} \cdot f_{m,d}} \leq 1 \tag{7.27}$$

With:

$$\begin{aligned} \sigma_{m,d} &= \frac{M_{f,y}}{\frac{b_w\,h_w^2}{6}} \\ &= \frac{\frac{(1.5 \cdot 1.5t) \cdot 1.875m}{4}}{\frac{0.35m \cdot 0.1m^2}{6}} \\ &= 9.04MPa \end{aligned} \tag{7.28}$$

$$\begin{aligned} f_{m,d} &= f_{m,k} \cdot k_{sys} \cdot k_h \cdot \frac{k_{mod}}{\gamma_M} \\ &= 35 \cdot 1.1 \cdot \min\left(1.3; \left(\frac{150}{100}\right)^{0.2}\right) \cdot \frac{0.5}{1.3} \\ &= 16.05MPa \end{aligned} \tag{7.29}$$

$$\begin{aligned} \sigma_{m,crit} &= \frac{0.78\,E_{0.05}\,b_w^2}{h_w\,L\,k_{ef}} \\ &= \frac{0.78 \cdot 8700 \cdot 0.4^2}{0.1 \cdot 1.875 \cdot 0.8} \\ &= 6238MPa \end{aligned} \tag{7.30}$$

k$_{ef}$ is equal to 0.8 in the case of a single load on a simply supported beam.

Therefore,

$$\begin{aligned}\lambda_{rel,m} &= \sqrt{\frac{f_{m,k}}{\sigma_{m,cit}}} \\ &= \sqrt{\frac{35}{7238}} \\ &= 0.07 < 0.75\end{aligned} \tag{7.31}$$

$$k_{crit} = 1 \tag{7.32}$$

Criteria is verified:

$$\frac{\sigma_{m,d}}{k_{crit} \cdot f_{m,d}} = \frac{9.04}{1 \cdot 16.05} = 0.56 < 1 \tag{7.33}$$

7.6.3 ULS: resistance of the tenon

The last wooden element to be check is the resistance of the tenon to the shear force V acting on it when one of the plank is loaded by a wheel at ULS:

$$V = \frac{Q}{2} = 1.5 \cdot \frac{1.5\,t}{2} = 1.125\,t \tag{7.34}$$

At ULS, for a tenon whose height and width are $b_t = 20$ cm and $h_t = 5$ cm, verification states:

$$\frac{\tau_d}{f_{v,d}} \leq 1 \tag{7.35}$$

With:

$$\begin{aligned}\tau_d &= \frac{V}{b_t\, h_t} \\ &= \frac{1.125\,t}{0.2\,m \cdot 0.05\,cm} \\ &= 1.125 MPa\end{aligned} \tag{7.36}$$

$$\begin{aligned}f_{v,d} &= f_{v,k}\frac{k_{mod}}{\gamma_M} \\ &= 3.4 \cdot \frac{0.5}{1.3} \\ &= 1.3 MPa\end{aligned} \tag{7.37}$$

Criteria is verified:

$$\frac{\tau_d}{f_{v,d}} = \frac{1.125}{1.3} = 0.87 < 1 \tag{7.38}$$

7.7 Reinforced concrete elements

7.7.1 Overlapping

Minimal overlapping of reinforcement is defined in section 8.7.5 of EN 1992-1-1, for welded wire meshes of the distribution reinforcement (circumferential direction corresponds to the secondary mesh).

According to the prospect 8.4, for $6 \leq \phi \leq 8.5$, overlapping must exceed 250 mm. In the principal direction, overlapping is l_0, as stated in equation 8.10 of EC2, section 8.7.3:

$$l_0 = \alpha_1\, \alpha_2\, \alpha_3\, \alpha_5\, \alpha_6\, l_{b,rqd} \geq L_{0,min} \tag{7.39}$$

Typical values are:

- $\alpha_1 = 1$ for straight bars;
- $\alpha_2 \leq 1$ (conservative value);
- $\alpha_3 \leq 1$ (conservative value);
- $\alpha_5 \leq 1$ (conservative value);
- $\alpha_6 \leq 1.5$ (conservative value);
- $l_{b,rqd} = \frac{\phi}{4}\frac{\sigma_{sd}}{f_{bd}} = \frac{7}{4}\frac{\sigma_{sd}}{2.25 \cdot 1.2} = 0.65 \cdot \sigma_{sd}$ [mm];
- $l_{0,min} = \min(0.3\, \alpha_6\, l_{b,rqd};\ 15\phi;\ 200\, mm)$;

$$l_0 \approx min\,(200\, mm;\ \sigma_{sd}\ [mm])$$

with $\sigma_{sd} \leq 391\, MPa$, giving for $l_{0,max} = 40$ cm.

7.7.2 Analysis of the section

A cross-section can be modelled as shown on Fig. 7.4. The corresponding disposition gives the minimal bending abilities, as any in-plane rotation of the section would raise the resisting moment and increase the participation of tensile steel. Longitudinal bars are separated by an angle 48°, except for internal overlapping layer, for which angular distance raises to 55°.

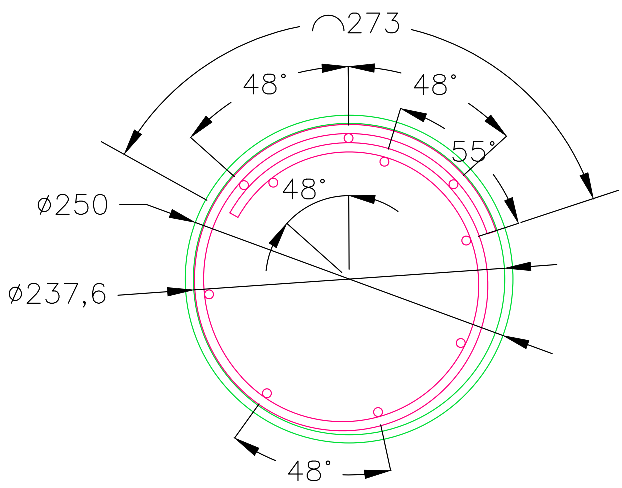


Figure 7.4: Main quantities of the confined reinforced concrete section.

The section is modelled adimensionally, assuming an internal diameter of 2 (scale factor is $D_i/2$).

Minimal reinforcement.
According to EC2 section 9.2.1, the area of longitudinal reinforcement has to be greater than the minimal reinforcement $A_{s,min}$, whose value is given by Eq. 7.40:

$$A_{s,min} = 0.26\,\frac{f_{ctm}}{f_y}\,b_t\,d \leq 0.0013\,b_t\,d \qquad (7.40)$$

With:

- $f_{ctm} = 2.1$ MPa;
- $f_y = 450$ MPa;
- b_t is the average with of the tensile zone;
- d = 227.1 mm, as calculated in 7.7.4;

This requirement will be verified for each element at ULS Bending (section 7.7.3).

Sectional quantities.
Let define the following numbers:

- x the neutral axis of the section defined with respect to its center of gravity. add drawing of the section;
- A_{compr} the area of compressed concrete;
- A_1 the area comprised between the radii of angle $\pm \arcsin x$;
- A_2 the area of A_1 comprised between central axis and neutral axis;
- P_i the internal diameter of a tube: $P_i = \Pi\, D_i = 746$ mm;
- e = 10 cm the spacing of the bars in circumferential direction;
- $N_b = \dfrac{P_i}{e} = 7.5$ the number of longitudinal reinforcing bars;
- $\alpha_b = \dfrac{360}{N_b} = 48°$ the angle between two consecutive bars;
- $d_i = \cos(\alpha_i)\frac{R_i - 1.5\phi}{R_i}$ the distances of the center of gravity of the bars with respect to central axis;
- $h_i = d_i - x$ the distances of these bars to the neutral axis of the section;

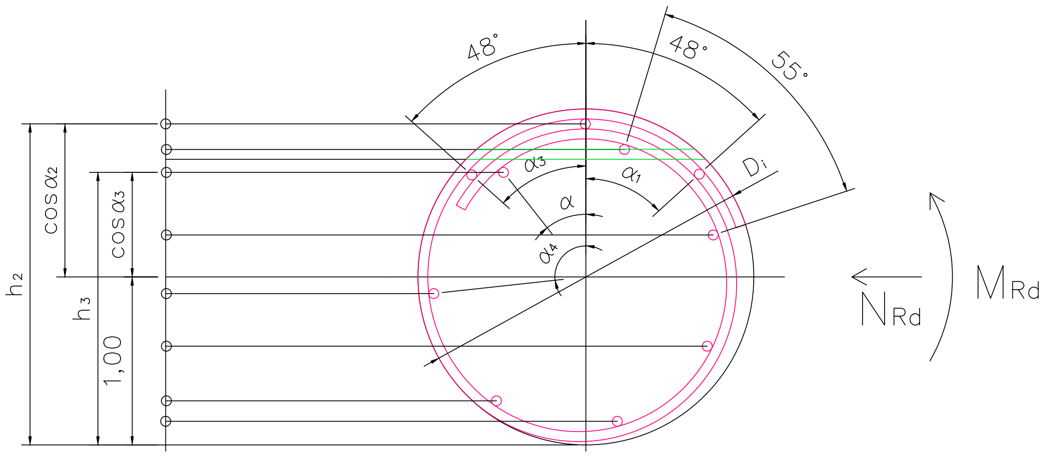


Figure 7.5: Geometrical quantities of the reinforcement.

As shown on Fig. 7.7, a point of the circular section can be defined by its coordinates (r,α).

$$\cos(\alpha_i) = \cos(i\,\alpha_b\,\frac{180}{\Pi}) \tag{7.41}$$

If failure occurs for steel, then, according to Navier-Bernoulli hypothesis of linear strains:

$$\epsilon_{s,max} = \epsilon_{su} = \frac{f_{yd}}{E_s} \approx 0.002 \tag{7.42}$$

Curvature is:

$$(1/r)_s = \frac{\epsilon_{su}}{h_{max}} \tag{7.43}$$

If concrete fails, $\epsilon_{s,max} = \epsilon_{cu} = -0.0035$ and curvature is:

$$(1/r)_c = \frac{-\epsilon_{cu}}{1-x} \tag{7.44}$$

Deformations at a distance z from central axis ϵ(z) write:

$$\epsilon(z) = (x-z)(1/r) \tag{7.45}$$

In particular, for the steel bars, stresses and strains come as:

$$\epsilon_{si} = h_i\,(1/r) \qquad \& \qquad \sigma_{si} = E_s\,\epsilon_{si} \tag{7.46}$$

Areas of concrete.

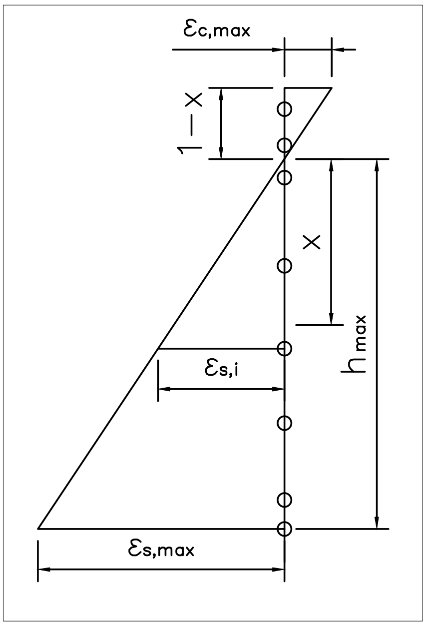


Figure 7.6: Strains in the hypothesis of Navier-Bernoulli

With reference to Fig. 7.7 ($\lambda = 0.8$), the area of concrete results:

$$\begin{aligned} A_1(x) &= \int_{-\arccos(x)}^{\arccos(x)} \int_0^1 r.d\theta.dr = \arccos(x) \\ A_2(x) &= x\,y = x\sqrt{1-x^2} \\ A(x) &= A_1(x) - A_2(x) \\ A_{compr}(x) &= A(\lambda x + (1-\lambda)) = A(0.8x + 0.2) \\ A_{s,i} &= \frac{\Pi\,\phi^2}{4} 38,5\,mm^2 \end{aligned} \tag{7.47}$$

Moments of inertia.
With respect to central axis, the moment of inertia is:

$$\begin{aligned} W_1 &= \int_{-\arccos(x)}^{\arccos(x)} \int_0^1 r.d\theta.r.cos(\theta).dr = \frac{1}{3}\,2\sin(\arccos(x)) = \frac{2}{3}\sqrt{1-x^2} \\ W_2 &= x\,y\,\frac{2\,x}{3} = \frac{2\,x^2}{3}\sqrt{1-x^2} \\ W(x) &= W_1(x) - W_2(x) \\ W_{compr} &= W(\lambda x + (1-\lambda)) = W(0.8x + 0.2) \\ W_{s,i} &= A_{s,i} sin(\alpha_i) \end{aligned} \tag{7.48}$$

Therefore, the coordinate of the center of gravity is derived as:

$$y_{G,c} = \frac{W_{compr}}{A_{compr}} \tag{7.49}$$

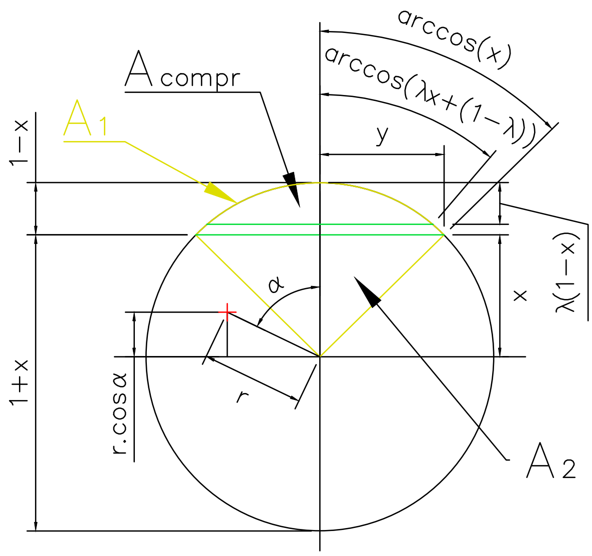


Figure 7.7: Geometrical quantities of the concrete section.

7.7.3 Bending

To assess a section at bending ULS, the (N_{Ed},M_{Ed}) state of the section has to stand within the diagram (N_{Rd},M_{Rd}): the following equation is a sufficient condition to ensure safety:

$$M_{Rd} \geq M_{Ed} \qquad with\ N_{Rd} = N_{Ed} \tag{7.50}$$

Horizontal equilibrium.

$$N = f_{cd}\, A_c + \sum_{i=0}^{N_i - 1} A_{si}\, \sigma_i \tag{7.51}$$

This equation allows to determine the position of neutral axis x.

Rotational equilibrium at the neutral axis of the section.

$$M_{Rd} = -f_{cd}\, A_c\, y_{G,c} - x + \sum_{i=0}^{N_i - 1} A_{si}\, \sigma_i\, \sin(\alpha_i) \tag{7.52}$$

Tab. 7.8 shows for each ULS load case and elements the maximal resisting moment, for $N_{Rd} = N_{Ed}$:

Therefore all sections are checked at ULS of bending. Any rotation of the section described previously would raise the resisting moment as it would bring more reinforcing bars in the tensile part of the section. This means the section can be set in an indifferent configuration.

Element	Loading Case	**N** [kN]	**M** [kN]	$\mathbf{M}_{Rd}$ [kN]	**x** [-]
Deck	LC1	-25.3	17.2	28.7	0.594
	LC2	-175.2	2.1	45.9	0.193
	LC5	-18.9	2.1	28.2	0.615
	LC6	-18.8	17.2	28.2	0.616
CPI	LC1	1.7	0.5	26.7	0.686
	LC2	14.3	0.8	25.9	0.733
CPS	LC1	8.5	5.3	26.3	0.711
	LC2	0.0	8.3	26.9	0.680
Col.	LC1	-0.2	21.4	26.9	0.679
	LC2	0.6	5.5	26.8	0.682
	LC5	-0.2	1.5	26.9	0.679
	LC6	-0.1	21.4	26.9	0.680

Table 7.8: Bending resistance M_{Rd} of the elements (Deck, CrossPiece Inf. or Sup, Columns).

7.7.4 Shear

According to EC2 section 6.2, if

$$V_{Ed} \leq V_{Rd,c} = [C_{Rd,c}\, k\, (100 \rho_l f_{ck})^{0.3} + k_1\, \sigma_{cp}] b_w\, d \tag{7.53}$$

then no special shear reinforcement is necessary. Eq. 7.53 mentions:

- $C_{Rd,c} = \frac{0.18}{1.5} = 0.12$ as recommended;
- d is the maximal distance between a reinforcing bar and the edge of a section: $d = D_i - 1.5\phi = 227.1$ mm;
- $k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$: $k = 1.94$;
- $b_w = D_i = 237.6$ mm is the width of the tensile part of concrete;
- $A_{sl} = N_i A_{s,1} = 11 \cdot \frac{\Pi \phi^2}{4} = 423.3 mm^2$
- $\rho_l = \frac{Asl}{b_w\, d} = 0.78$ %
- $\sigma_{cp} = \frac{N_{Ed}}{A_c} < 0.2\, f_{cd}$ is the compressive stress due to axial compression, based on the area A_c of a beam;
- $k_1 = 0.15$;

Tab. 7.9 presents computed values of $V_{Rd,c}$ for each element and load case, calculated from efforts N and V of Tab. 7.2 and Tab. 7.5. It can be deduced that every element is verified at ULS for shear and that no special shear reinforcement is needed, as Eq. 7.53 is checked.

Element	**Loading Case**	**N** [kN]	**V** [kN]	σ_{cp} [MPa]	$V_{Rd,c}$ [kN]
Deck	LC1	-25.3	30.3	0.57	35.3
	LC2	-175.2	10.9	-5.5	53.6
	LC5	-18.9	2.1	-2.1	34.1
	LC6	-18.8	29.6	-15.1	34.1
CPI	LC1	1.7	0.1	-0.6	30.7
	LC2	14.3	0.1	0.0	30.7
CPS	LC1	8.5	2.0	0.0	30.7
	LC2	0.0	17.4	0.0	30.7
Col.	LC1	-0.2	20.0	0.0	30.7
	LC2	0.6	14.4	0.0	30.7
	LC5	-0.2	2.5	0.0	30.7
	LC6	-0.1	19.7	0.0	30.7

Table 7.9: Shear resistance $V_{Rd,c}$ of the elements (Deck, CrossPiece Inf. or Sup, Columns), without special shear reinforcement.

7.7.5 Instability

Instability is mostly critical for deck elements, as they are the most compressed. They can be considered clamped, because of the presence of reinforcing bars. Critical effort is then approximately for an homogeneous section:

$$N_{cr} = \frac{4\Pi^2\, E\, I}{L^2} \tag{7.54}$$

Considering a length of 1.875 m, long-term Young modulus E = 10 GPa and modulus of inertia I $=\dfrac{\Pi\, D_i^4}{64} = 1.56\,\text{x}10^{-4}\, m^4$, it comes:

$$N_{cr} = \frac{4 \cdot \Pi^2 \cdot 10,000 \cdot 1.56\, 10^{-4}}{1.875^2} = 17,500\, kN \tag{7.55}$$

Most important compressive force is minor than 200 kN, as shown in Tab. 7.2, hence safety is largely ensured.

7.7.6 Limitation of stress

Stress in a reinforced concrete beam can be calculated conservatively as in equation 7.1. In this case, for some elements, tensile capacity of concrete f_{ctm} = 2.1 MPa is

exceeded.
The admissible stresses are:

- for concrete:
$$\sigma_{c,min} = 0.45\, f_{ck} = 11.25MPa$$

- for reinforcing steel:
$$\sigma_{s,max} = 0.8\, f_{yk} = 360MPa$$

- for the cable:
$$\sigma_{s,max} = 0.75\, f_{pk} = 1230MPa$$

  It will therefore be verified that, at SLS, the normal effort in the cable does not exceed:
$$0.75\,\frac{N_{cr}}{5} = 185.25kN$$

As shown in tab. 7.2 and Tab. 7.5, compressive linear stress (taking into account a linear stress is conservative as it leads to consider the section as homogeneous and to neglect the contribution of steel) in concrete does not exceed 11 MPa. Tab. 7.6 shows that requisitions are also verified for the cable.
Finally, maximal efforts in the reinforcing bars can approximately and conservatively be calculated as:
$$\sigma_{max,s} = \frac{E_s}{E_c}\sigma_{max,c} \tag{7.56}$$
Taking $E_s = 200$ GPa and $E_c = 31$ GPa, maximal stress in reinforcing steel computed this way is 103.5 MPa, for LC1 on the columns.
Limit state of limitation of stress is verified.

7.7.7 SLS: Cracking

Without special requirement, values of w_{max} from table 7.1N of EC2 are adopted: in particular, $w_{max} = 0.4$ mm for normal reinforced concrete and pre-stressed elements with non adherent cables.
In tables 7.2N and 7.3N of Eurocode 2 are given values of maximal diameter ϕ_s^* and maximal spacing of the reinforcing bars to ensure control of the cracking width. These values are conservative.
As shown in section 7.7.6, maximal stress in steel is lower than 160 MPa at SLS. Hence, maximal diameter and spacing to limit w_k to 0.4 mm are respectively 40 mm and 300 mm. Implemented data is:

- $\phi = 7$ mm;

- $e_b = 0.1$ m $= 100$ mm.

Taking into account that PVC tubes ensure sealing against exterior environment and that it provides a good cover to concrete, SLS of cracking is verified.

7.7.8 Limitation of deflection

This limit state is critical for superior crosspieces, as they bear the planking. Concrete beam can be considered clamped. Therefore, at SLS, total linear load q is the superposition of linear weight and linear variable load.
A traffic load would act only near the edges of the crosspieces and create little deflection at the center, as shown in section 6.2.3. It will not be determinant for this limit state.

The pedestrian loading results in a linear load q_q along the crosspieces, such as:

$$q_q = q\,L/8 = 500\,kg/m^2 \cdot 1.875\,m = 937.5\,kg/ml \tag{7.57}$$

Hence,

$$q = g_c + g_p + g_w + q_q = 125 + 7 + 111 + 937.5 = 1181 kg/ml \tag{7.58}$$

For the traffic load, deflection is created by an axle 2Q, each Q acting at $1/4^{\text{th}}$ of the crosspiece, at each side. It is equivalent to the deflection created by a single central Q. Admissible criteria is L/300 = 7.3 mm. Considering an homogeneous elastic concrete section, deflections at the center write at long-term (E = E_{lt} = 10000 MPa):

$$\begin{aligned} v_{L/2,2Q} &= \frac{Q\,L^3}{192\,E_{lt}\,I} \\ v_{L/2,q} &= \frac{q\,L^4}{384\,E_{lt}\,I} \end{aligned} \tag{7.59}$$

By substituting

$$\begin{aligned} v_{L/2,Q} &= \frac{15000 \cdot 2.2^3}{192 \cdot 10000 \cdot 0.15636} = 0.53\,mm \\ v_{L/2,q} &= \frac{11810 \cdot 2.2^4}{384 \cdot 10000 \cdot 0.15636} = 0.46\,mm \end{aligned} \tag{7.60}$$

Therefore SLS of Limitation of deflection is checked for the concrete elements.

7.8 Cable

The resistance of the cable is verified at ULS under LC1 and LC2. Maximal computed normal effort in the cable is N_{Ed} = kN. According to section 6.1.3, maximum admissible effort is N_{Rd} = 257 kN. Therefore, safety is ensured:

$$N_{Ed} = \; kN < N_{Rd} = 257\,kN \tag{7.61}$$

The cable is even over-dimensioned. However, a smaller cable would induce larger global deflections.

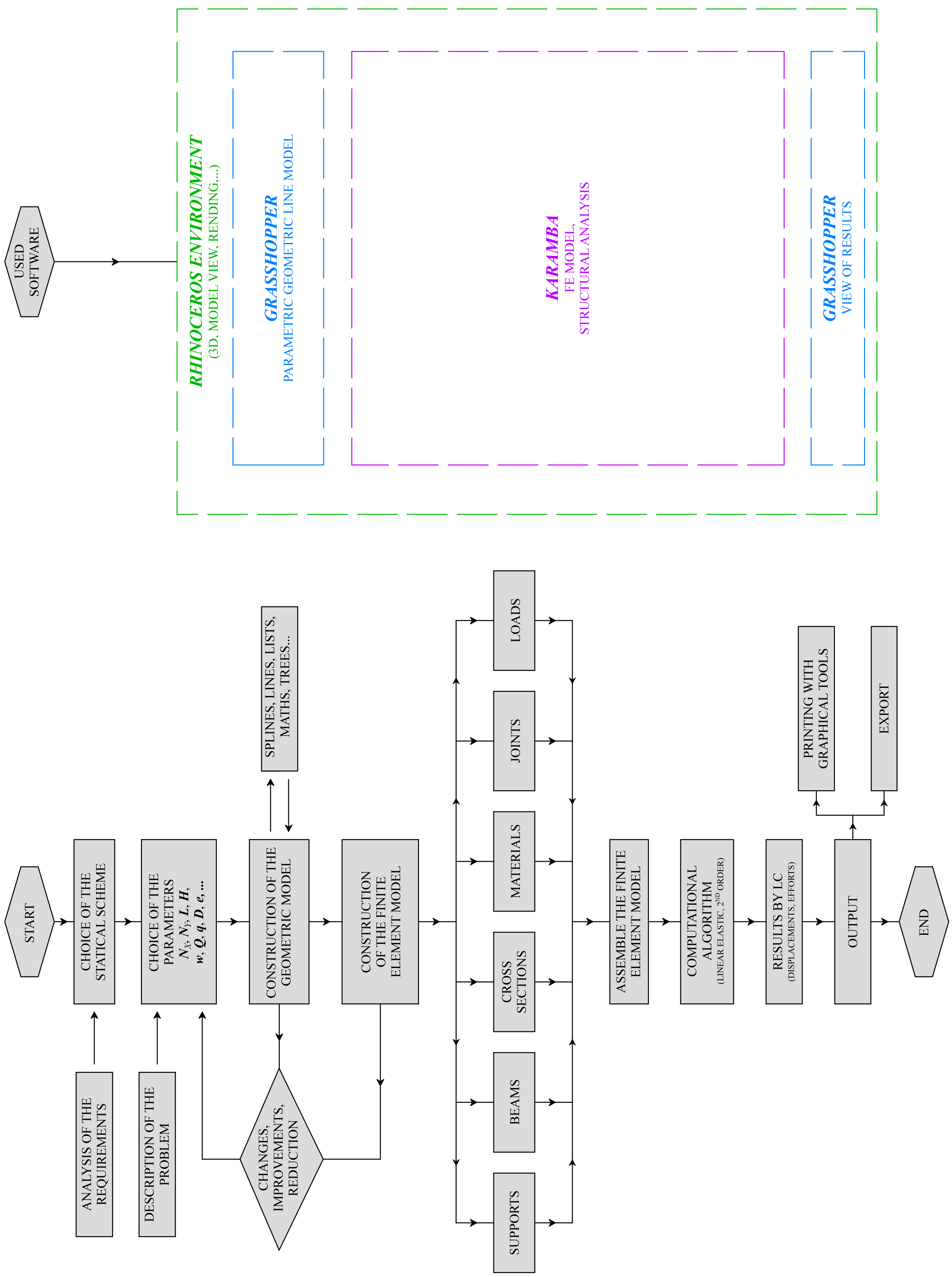


Figure 7.8: Flowchart.

Appendix A

Description of used software

In this attachment, the details concerning the software mentioned in the Thesis are discussed.

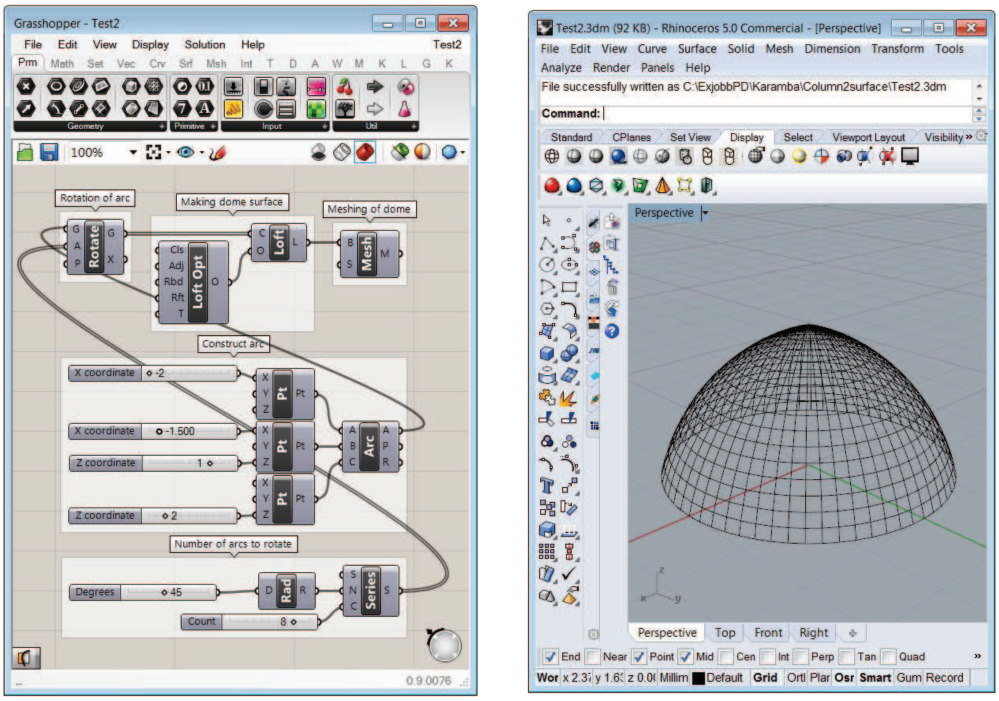
A.1 Rhinoceros

The *Rhinoceros or Rhino3D*, is a computer-aided design (CAD) and a 3-D modeler application software developed by Robert McNeel and Associates (McNeel *et al.*, 2015). The first version, Rhino 1.0, was released in October 1998. The geometry is based on NURBS (*Non-Uniform Rational B-Splines*) which focuses on producing 3-D free-form surfaces or solid and mathematically precise representation of curves. NURBS has a good flexibility and accuracy and can therefore be used in any process from illustration and animations to manufacturing. The geometry is an industry standard for designers who work in 3-D where both form and function is important. The models can be rendered at any resolution and a mesh can be crated from the model at any resolution.
Rhinoceros is primarily a free form surface modeller that utilizes the NURBS mathematical model. Its architecture makes it *modular* and enables the user to customize the interface and create custom commands and menus. There are dozens of plug-ins available, which complement and expand Rhinoceros' capabilities in specific fields like rendering and animation, architecture, marine, jewellery, engineering, prototyping, and others.
Rhino3D supports two scripting languages: Rhinoscript (based on VBScript) and Python. It also has a parametric modelling tool add-on: Grasshopper.

A.2 Grasshopper

The precursor to Grasshopper was born in 2008 and was then titled Explicit History. Later the same year it was re-branded to *Grasshopper*. It is developed by David Rutten at Robert McNeel and Associates (McNeel *et al.*, 2010). It uses a visual programming language (VPL) which, by manipulating logic elements graphically rather than by specifying them textually, lets users create programs. Grasshopper enables for designers to explore new shapes using generative algorithms, which is a combination of programming algorithms and geometry. The program is a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools as a plug-in and offers the opportunity to define precise parametric control over models.

Grasshopper is a platform for development of higher-level programming logic by using an intuitive, graphical interface and the capability to explore generative design work flows. The logic elements is functional blocks, so called components, that is added to a canvas. The components are connected by "wires" where the only syntax required is that the inputs of the blocks receive the data of the appropriate type. One can either design a geometry in Rhino3D and add it to the components in Grasshopper, or one can define the geometry in Grasshopper which in turn is shown and updated in Rhino3D's viewport wile changing parameters/components in Grasshopper. For example, in Fig. A.1 one can see a code for a dome in Grasshopper (a) that automatically updates in Rhino3D (b) wile changing parameters.



(a) Grasshopper.　　　　**(b)** Rhino3D.

Figure A.1: Software interface.

The algorithms are step by step procedures designed to perform an operation and when using Grasshopper the user designs these algorithms that then automate tasks in Rhino3D.

A.3 Karamba

Karamba is a Finite Element program which predicts how structures behave when subjected to external loads. It is fully embedded in the Grasshopper environment which makes it easy to combine geometric models, finite element calculations and optimization algorithms. Karamba takes full advantage of Grasshoppers visual computing environment and enables an instant update of the structural response when certain parameters are altered. The ability to get instant feedback on the structural performance, without additional software, gives a faster understanding of the structural mechanisms and reduces time in the design phase (Preisinger, 2010).
One reason for the speed of Karambas calculations are the deliberate limitations of the software e.g. instead of isoparametric finite beam elements Karamba uses hermitian elements which are confined to linear elastic calculations of elements with straight axes. The calculation of the element stiffness matrix can be done without the need for numeric integration which greatly reduces computation time. The advantage of the Hermitian element is that creating the element stiffness matrix (and element load vector) can be done in one analytical integration step. The global stiffness matrix is not inverted. Instead the global system is solved by triangular decomposition and backward and forward insertion. To be structurally useful the geometric entities needs to be converted to into structural elements.
Fig. A.2 shows the main parts of a model definition with Karamba where the geometry, a line between two points, is converted to a beam with a cross section, gravitational load, supports and material properties. The given conditions are then analyzed and the results can be viewed directly in the Rhino viewport with options common to standard FE programs (Preisinger and Heimrath, 2014).
Karamba offers several different ways of evaluating a structural model. The numerical evaluation options consists of second order theory, large deflections, eigenmodes, natural vibration modes, evolutionary structural optimization, cross section optimization and iterative elimination of tension or compression elements. For each calculation option there is a component which takes a model as input, calculates it and adds the results to the model data (Preisinger, 2010).
Karamba provides truss, beam and shell elements. The shell element formulation used in Karamba is based on the TRIC element with six DOFs per node, constant strain state assumed for each layer, no in-plane rotational stiffness added but contrary to the TRIC element it is based on Kirchhoff theory. The Finite Element Analysis (FEA) is performed with the assumption that deflections are small as compared to the size of the structure. There is however a component that enables calculations with large deflections which increases the load in several steps and updates the deformed geometry but this approach leads to a solution which drifts away from the exact solution.
Another assumption is linear elastic behaviour of the materials which suits the purpose of an initial design.
It is possible to do analysis with both first and second order theory in Karamba.

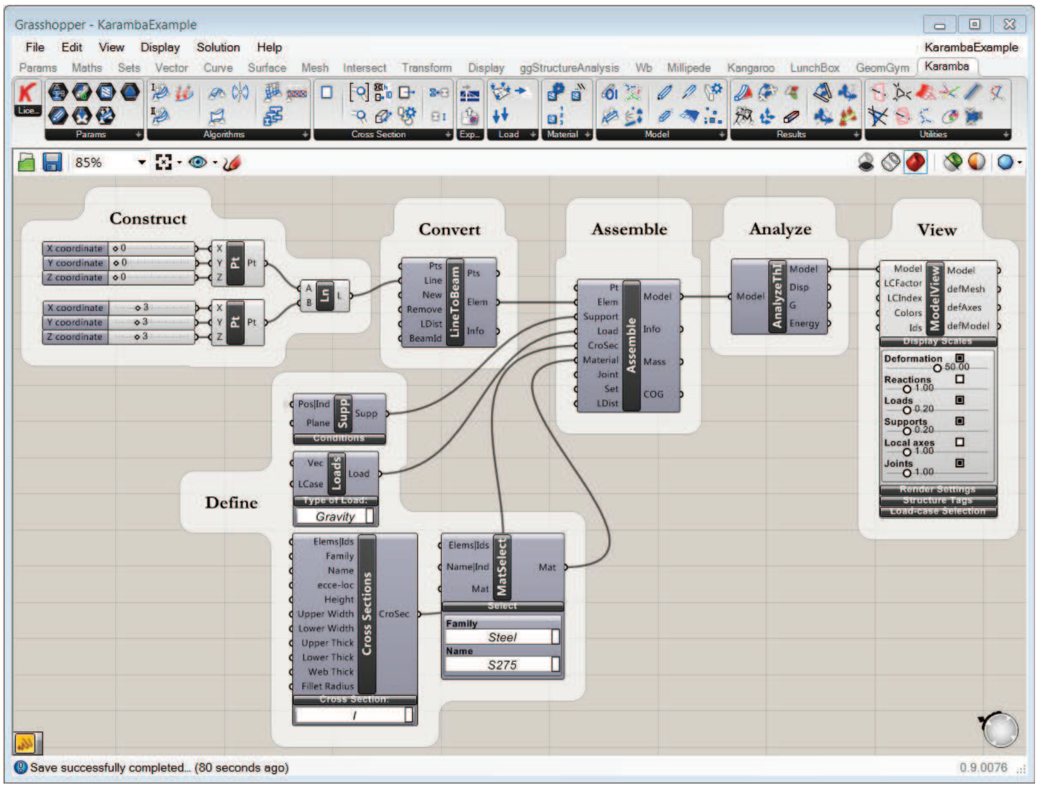


Figure A.2: Karamba workflow.

The big difference between the two is that the latter count for the influence of axial forces in beams and in-plane forces in shells. These two influence the structures stiffness. Also, compared to higher order theory, the first do not count for geometric non-linearity. Second order theory is considered with the use of the "AnalyzeThII" component. It accounts for axial forces via the element's geometric stiffness matrix and is based on small displacements.
Utilization of a analyzed structure or part in Karamba is calculated as Von Mises stress divided by the yield strength of the material. The results are possible for both beams and shells given as contour plots where the utilization is calculated in every element. Karamba only has components giving the maximum displacement of the analyzed structure which means that one has to define a Grasshopper/Karamba definition if one wants to find the deformation in specific nodes.

Creating a statical model in Karamba consists of six basic steps (Fig. A.3):

- **Create** wire-frame, point geometry or meshes for the structural model with Rhino or Grasshoper;
- **Convert** wire-frame or point geometry to Karamba beams, meshes to shells;
- **Define** which points are supports and which receive loads;

- **Assemble** the Karamba structural model with points, elements, supports and loads. As optional: Define custom cross sections and materials and add them as well. They reference elements either by index or user defined element identifiers;
- **Analyze** the Karamba structural model;
- **View** the analyzed model with the ModelView-component. Deflections can be scaled, multiple load cases can be viewed together or separately. The "BeamView" and "ShellView" components can be used to generate mesh representations of stresses, level of material utilization, ecc.

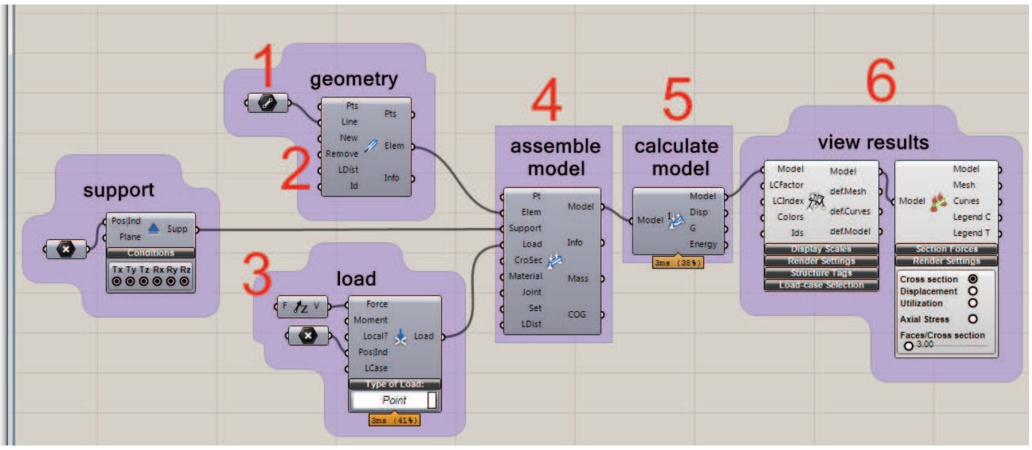


Figure A.3: Steps of a basic example in Karamba.

Karamba is being used in different types of research and projects, of which a lot are listed on the website [1]. An example is the temporary and wooden pavilion, designed and constructed by Manuel Fabian Hartmann and his team at the university of Innsbruck in 2013. The structural behavior of the physical model was investigated and optimized iteratively with Karamba. Another building project, by Falkeis Senn Architects, employs hybrid prefabricated column systems for dwellings which are designed and optimized with the use of Karamba. Karamba is also implemented for the parametric modelling and multi-objective shape optimization of a deployable origami-inspired shelter (Quaglia *et al.*, 2014).

[1] `http://www.karamba3d.com/examples`

Appendix B

Description of used software

In this attachment, the list of drawings is mentioned.

B.1 Drawings

The drawings of the footbridge are attached in the end of the document.

- Drawing n.1: Elevation and Plan View.
- Drawing n.2: Sectional Views.
- Drawing n.3: Sectional Views.
- Drawing n.4: Elevation, Section and Plan View of Supports.
- Drawing n.5: Planking Details.
- Drawing n.6: Planking Details.
- Drawing n.7: Details of Reinforcements.
- Drawing n.8: Details of Reinforcements.

Conclusions

Because of the depth of the initial objective, this work has discussed many aspects of the design of a footbridge. Among them, it has shown that the modular nature of a piping system is well suited to adapt several different static schemes. Piping system can be used to divide the design is structural phases, with PVC skeleton resisting permanent loads and concrete resisting to variable loads. Therefore, the intuition of using PVC concrete composite structures, which underlays this thesis, is applicable to many different types of structures. Two limits though shall be stated: they do not allow casting in place complex forms; crucial bearing elements in the present work are the steel cables.

Then, the structural abilities of PVC have been demonstrated. It provides an extra durability to concrete as it acts like a cover with respect to it and contributes to seal it from external environment and corrosive attacks. It has a behaviour similar to concrete. From the point of view of the resisting strength, it can be compared to a C25/30 concrete. However, it is far more deformable. Hence, it could probably not be used as a stand-alone material: a concrete matrix would still be needed to rigidify the structure.

Moreover, the realization of a scale model has made it possible to highlight dimensional compatibility problems of piping system. It also emphasized the poor mechanical properties of the fittings.

The execution studies assess the footbridge designed on strong basis; it helps learning about the implementation of PVC in civil engineering design process. They also underpin the advantages a parametric algorithm such as Karamba provides, and hopefully contributes to make it known from the engineering world, possibly striving synergies between architects and engineers in the design phase.

Even if the objectives of a 100% PVC structure have shown unrealistic, improvements with respect to the first attempt of 2015 have been made: PVC has been given a structural role, as it bears both wooden planking and concrete in concreting phase. No lifting machine has been used and all the elements are manhandling. Concreting is still made in a single phase, without construction joints in concrete.

Future prospects concern possible optimizations of the current static scheme: changing the orientation of the cable, it could be possible to compress crosspieces instead of extending it. From the point of view of implemented materials, an improvement would be the use, for domestic applications, of high-performance concrete, to avoid preparing and setting up reinforcement. One could also think about replacing concrete by a simpler filler, like aggregates, resisting to compression and burdening the bridge to avoid dynamic effects. Conjugated to the use of a more resistant PVC (such as PVC-C, with higher strength and modulus), a trade-off could be studied for the appropriate thickness of the tubes.

Finally, a satisfying answer shall not avoid the question of the intermediary supports. Improvements can be brought to provide a way to concrete the PVC skeleton without setting supports, to be able to cover more geographic situations.

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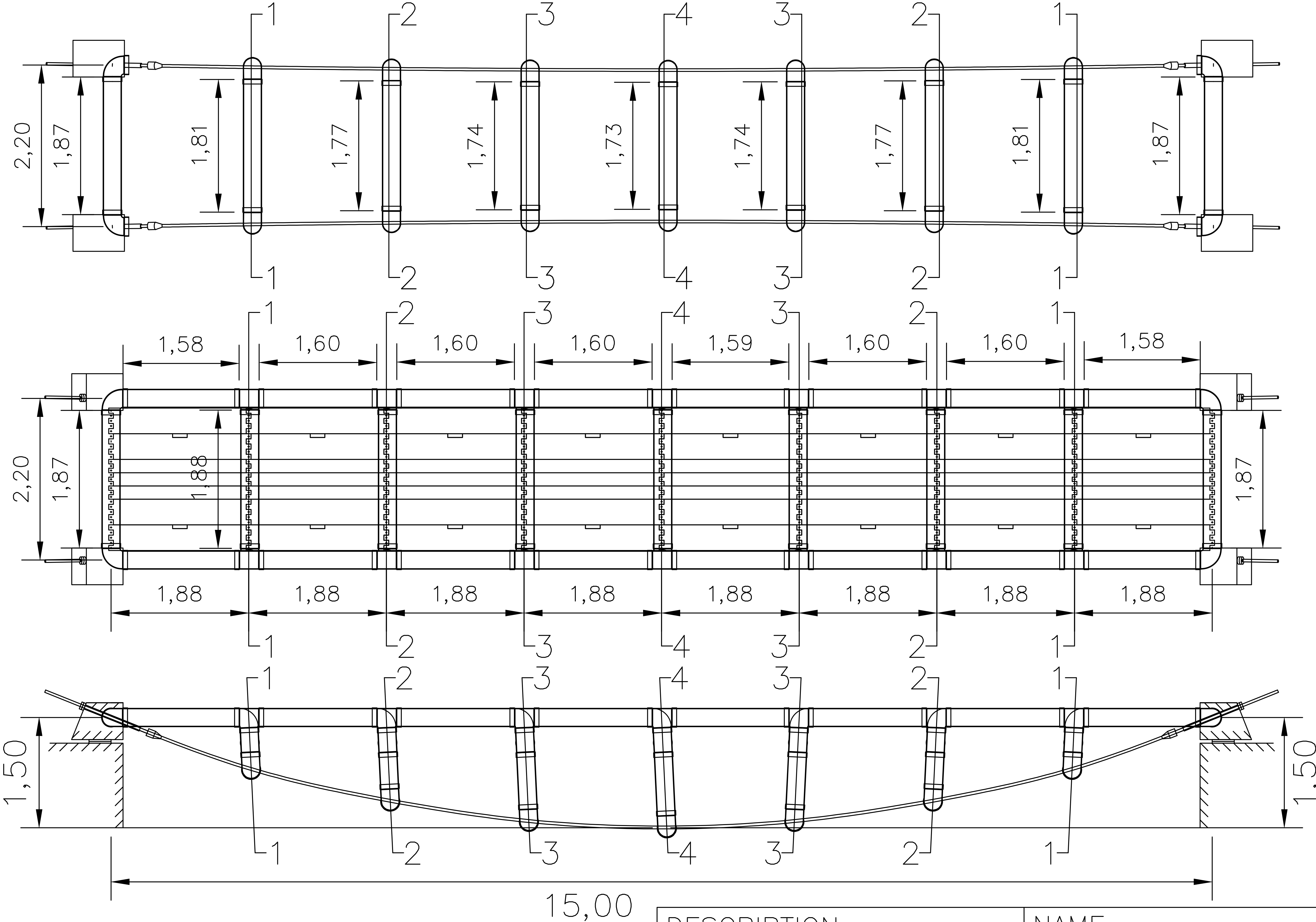

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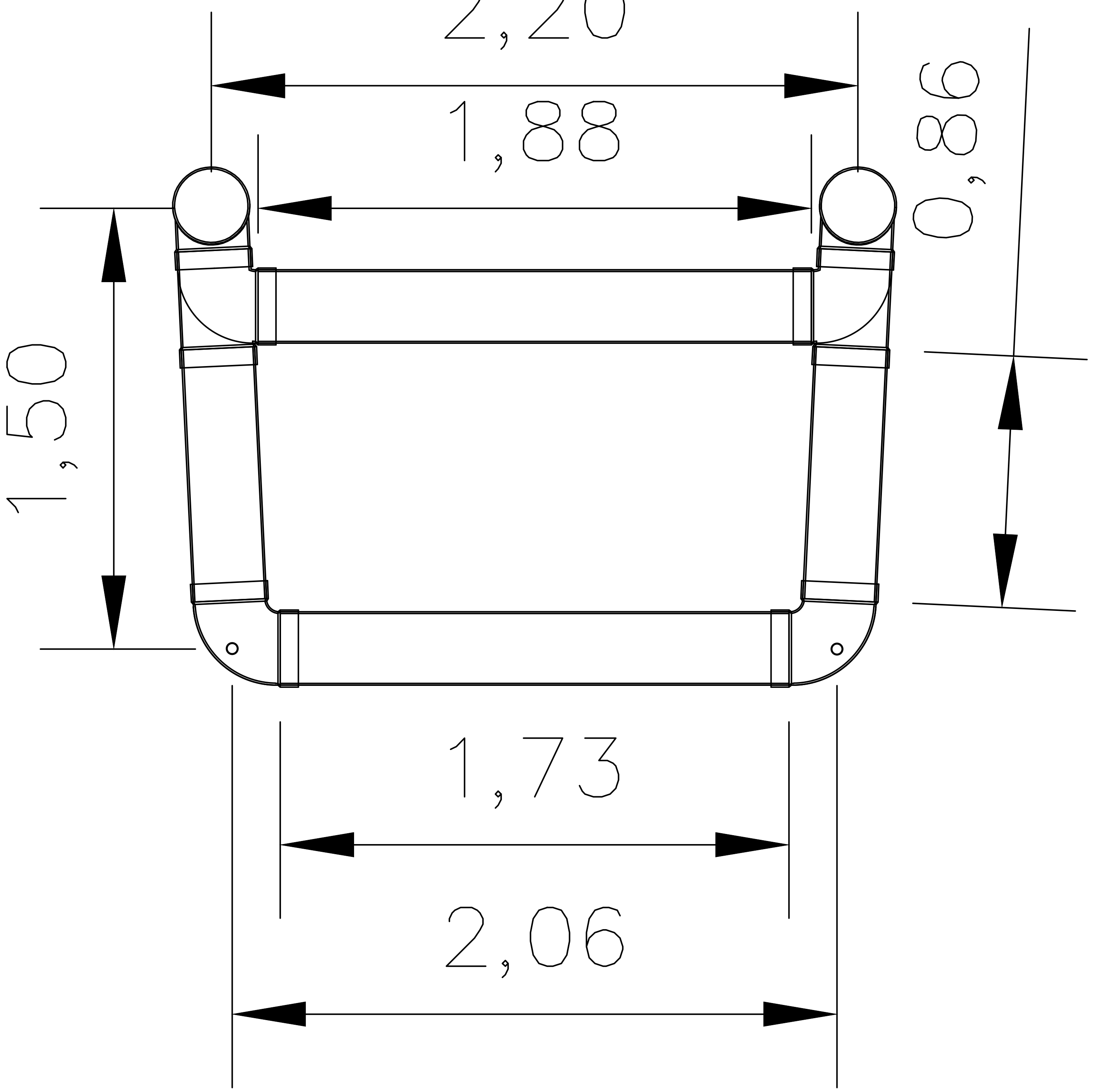

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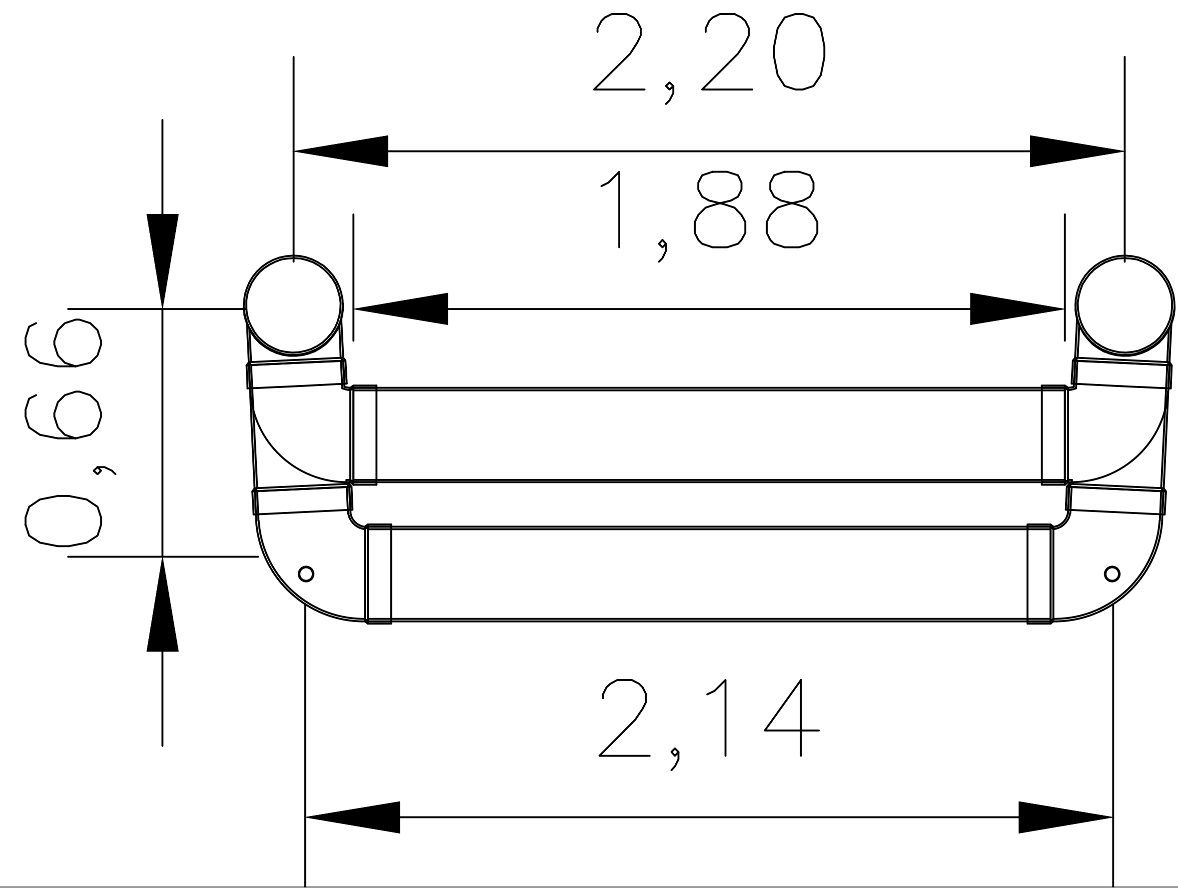

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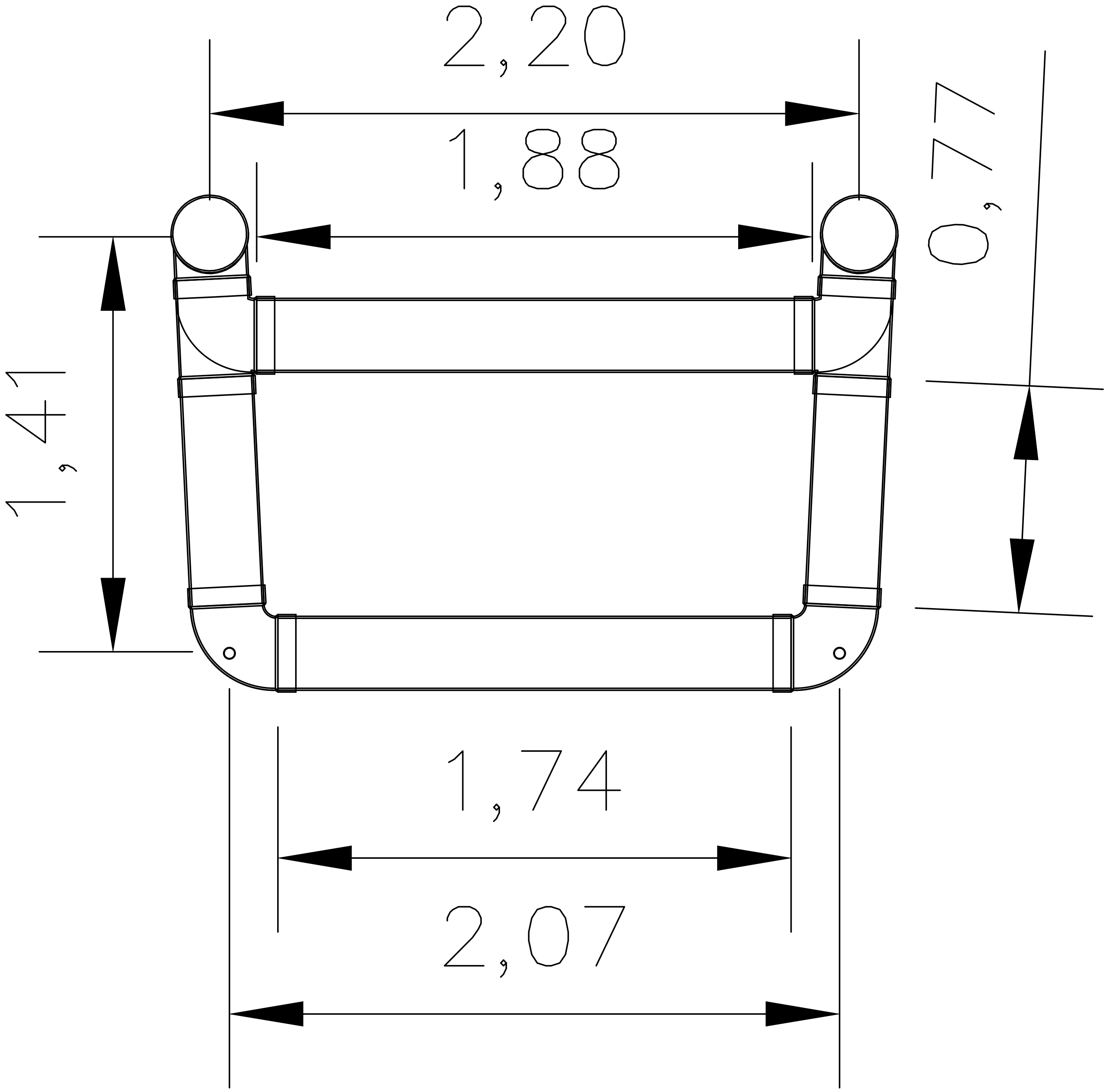

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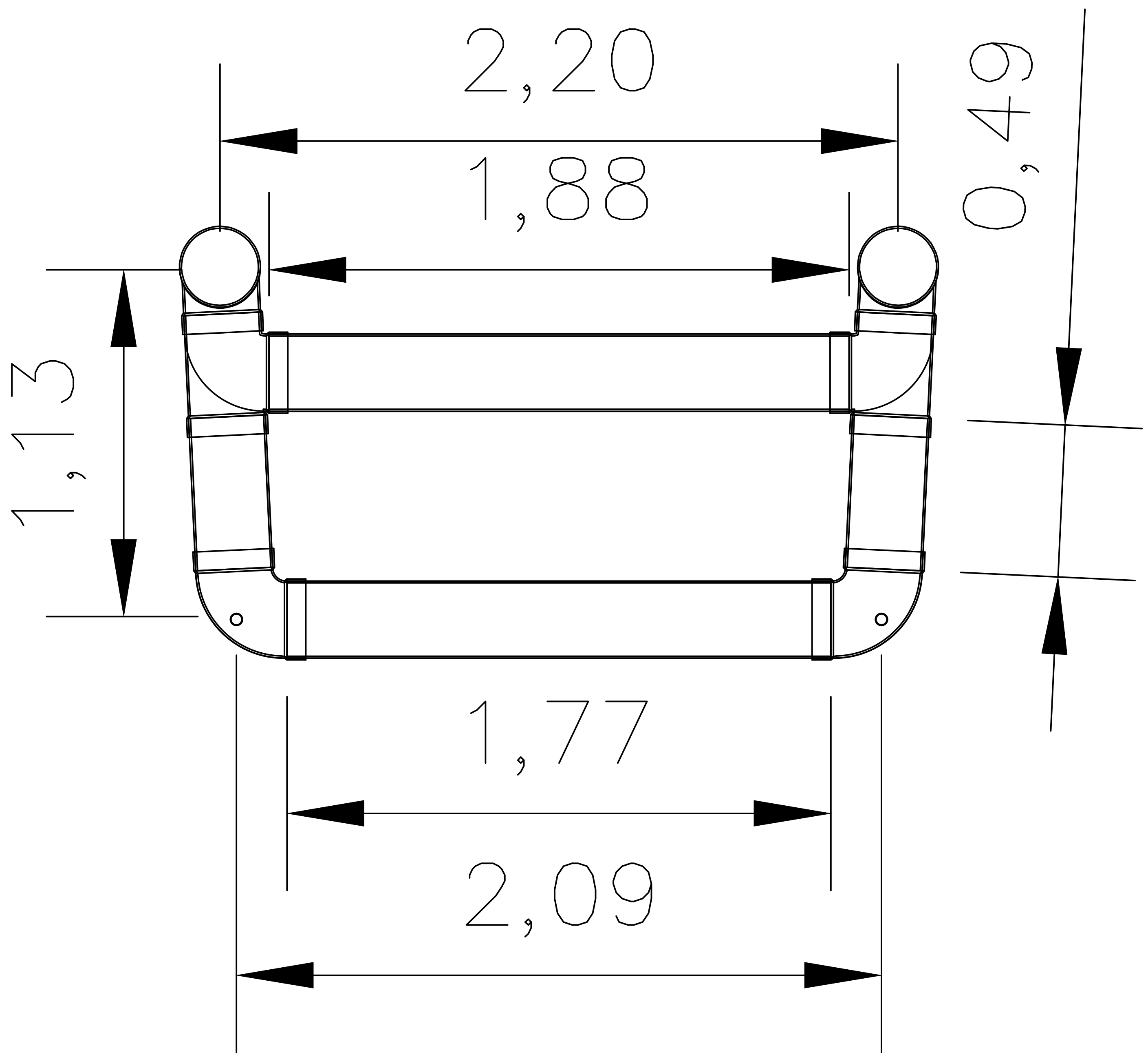

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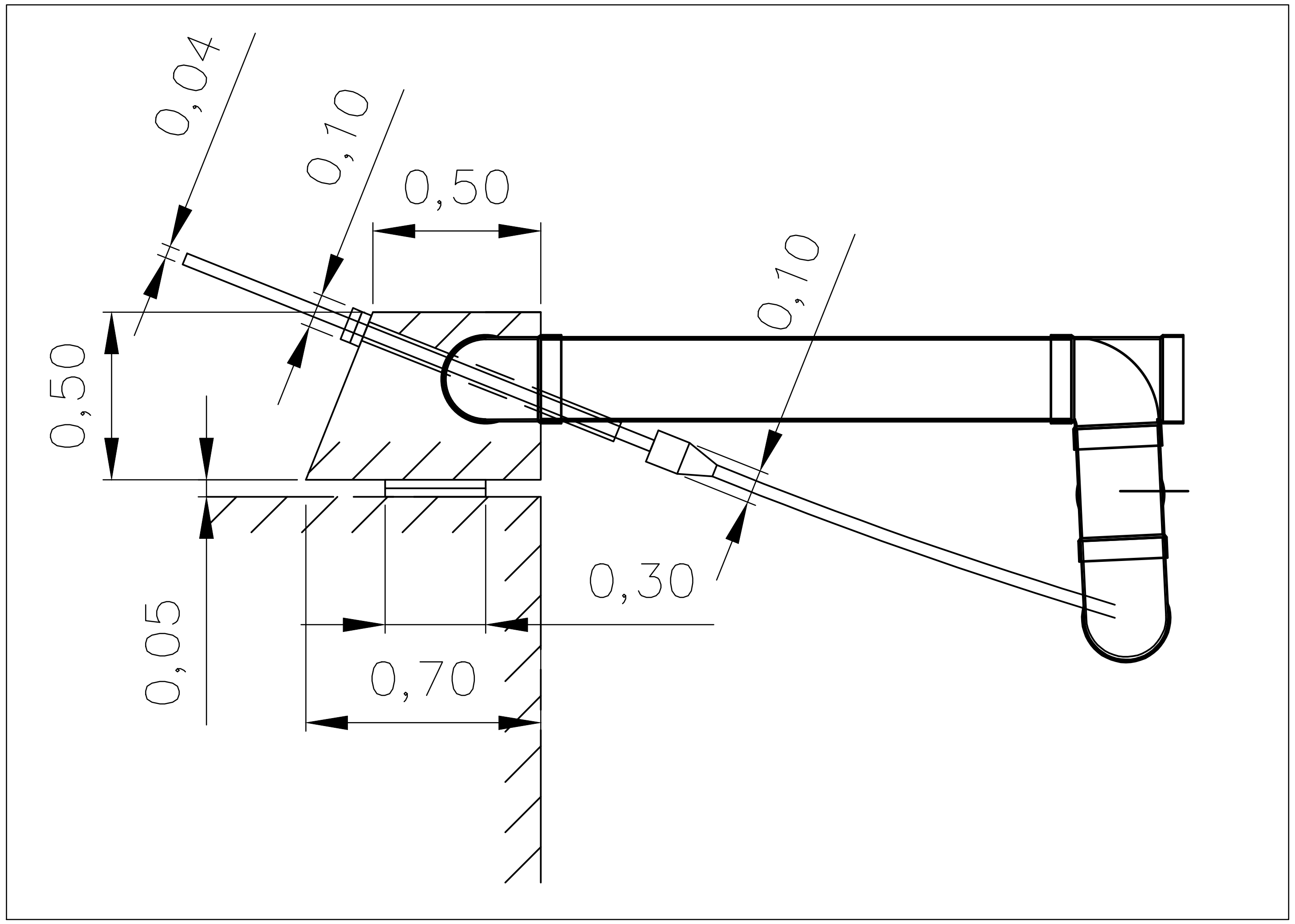

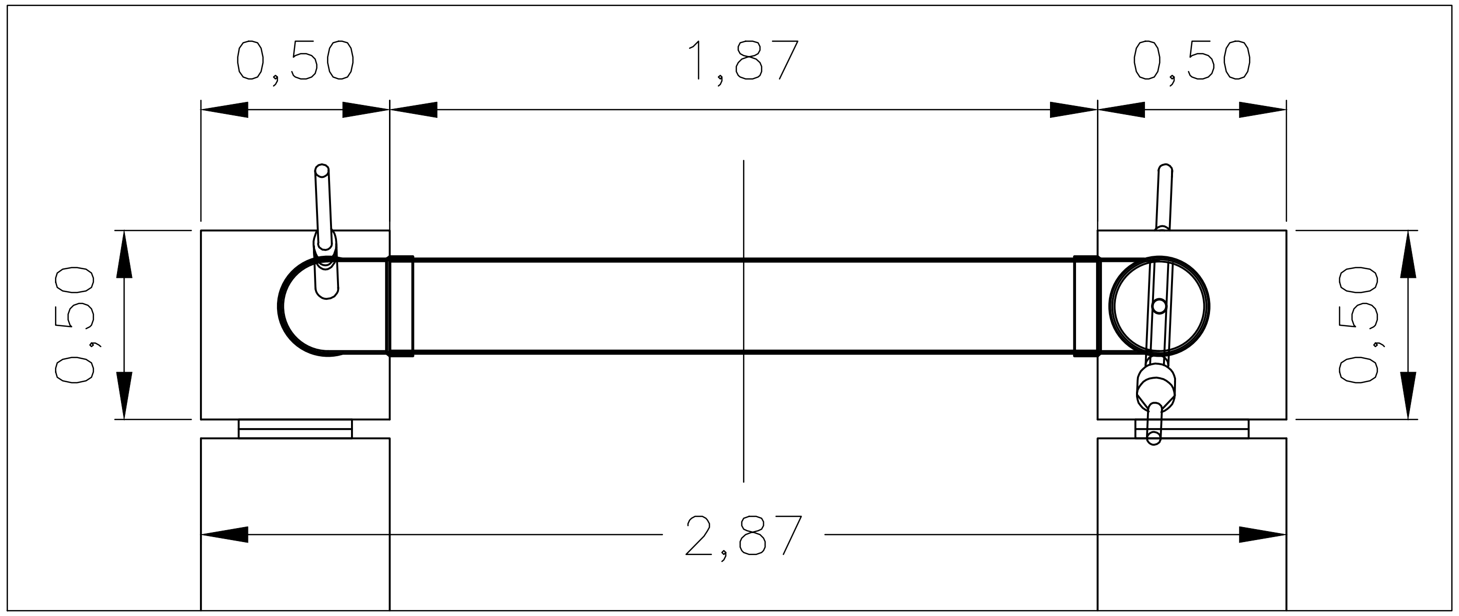

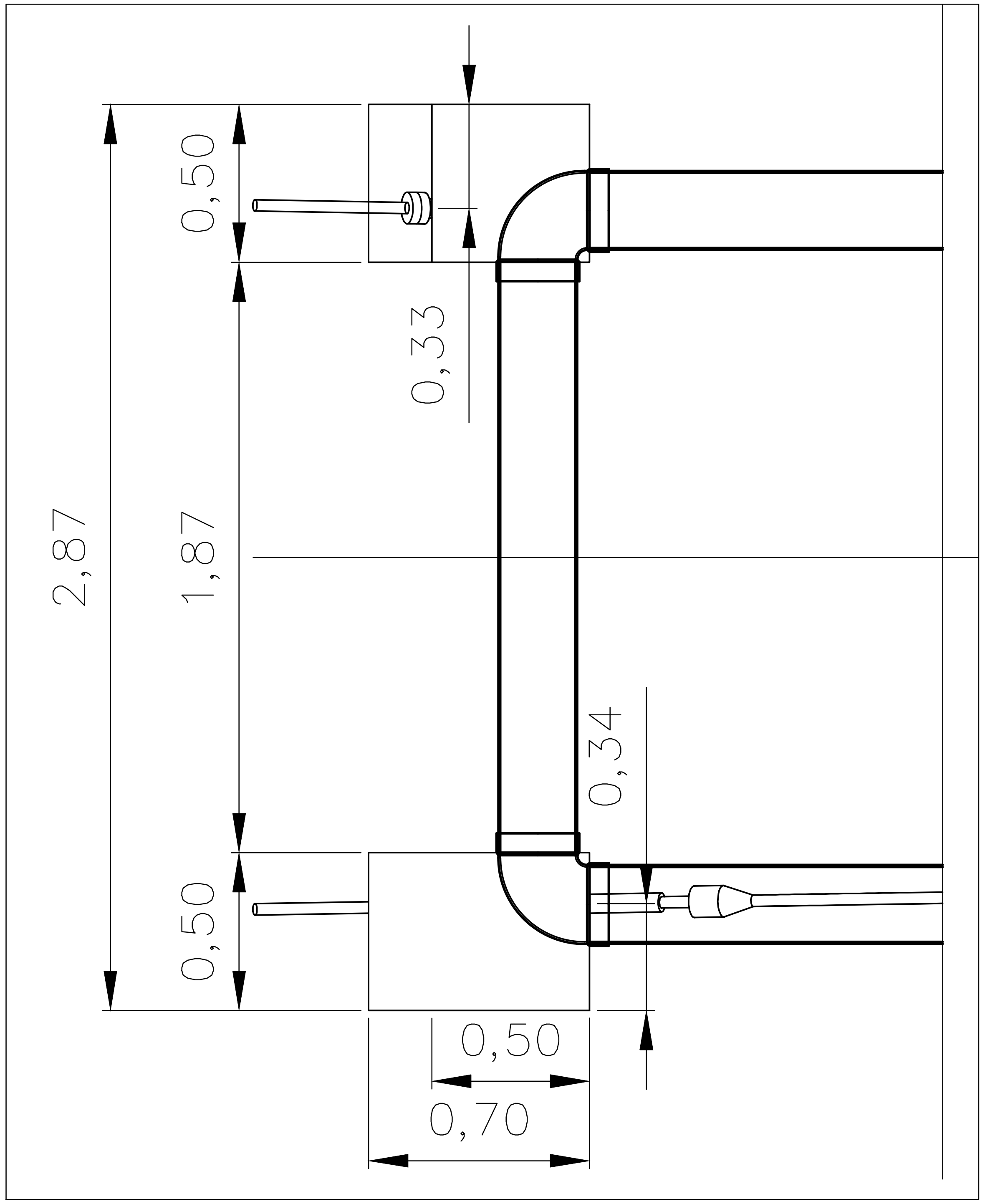

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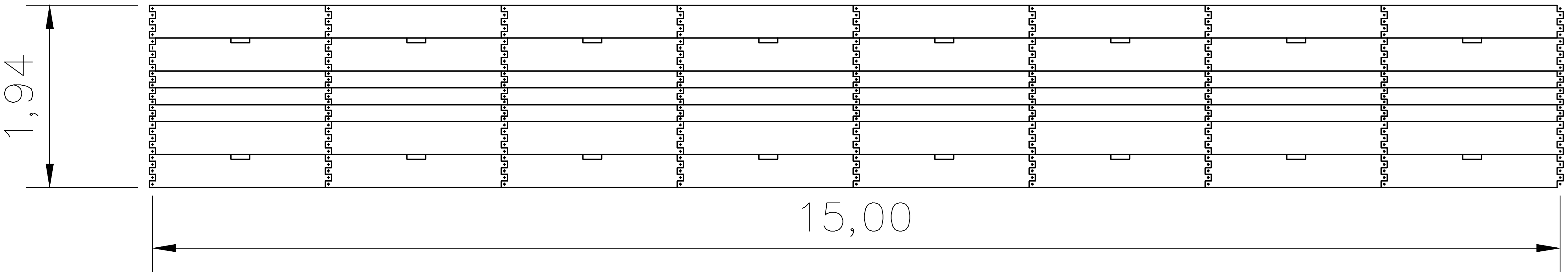

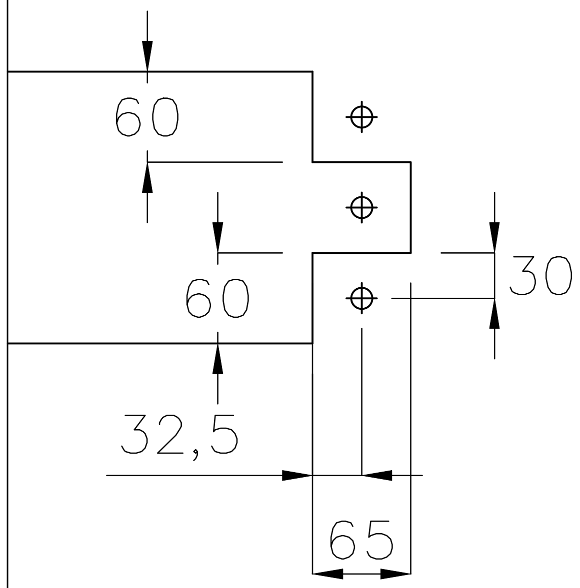

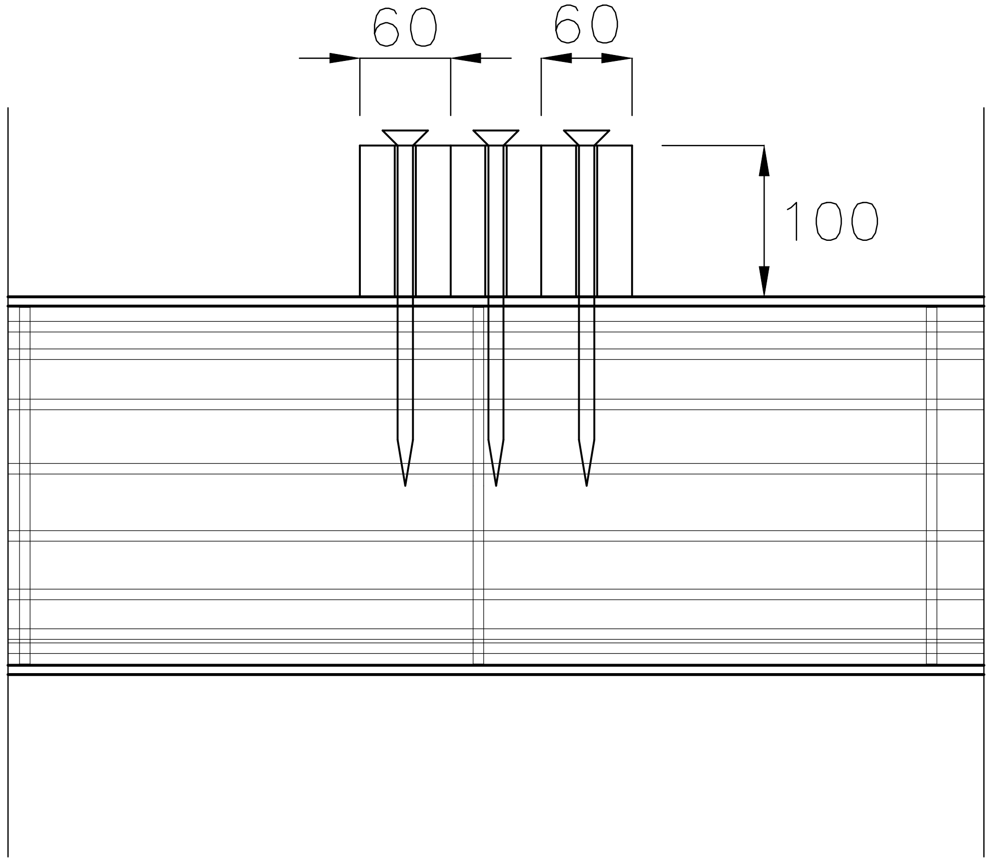

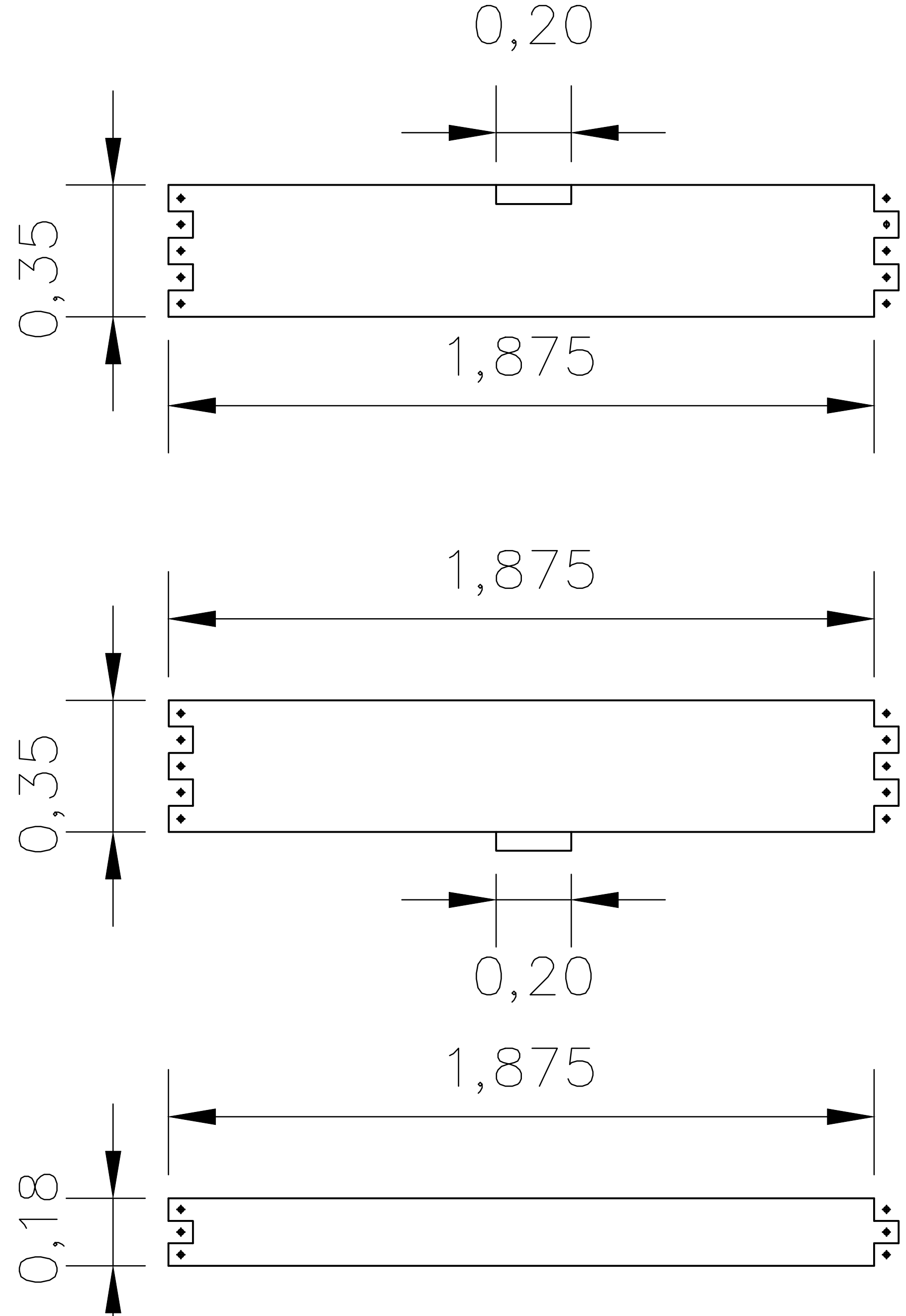

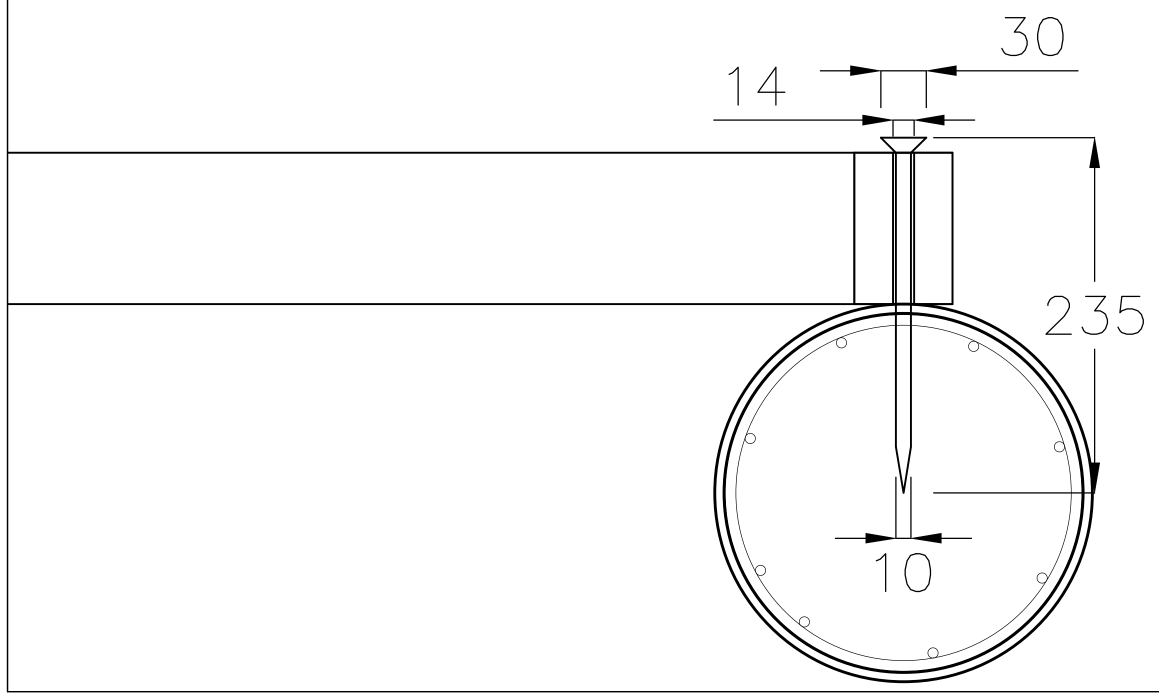

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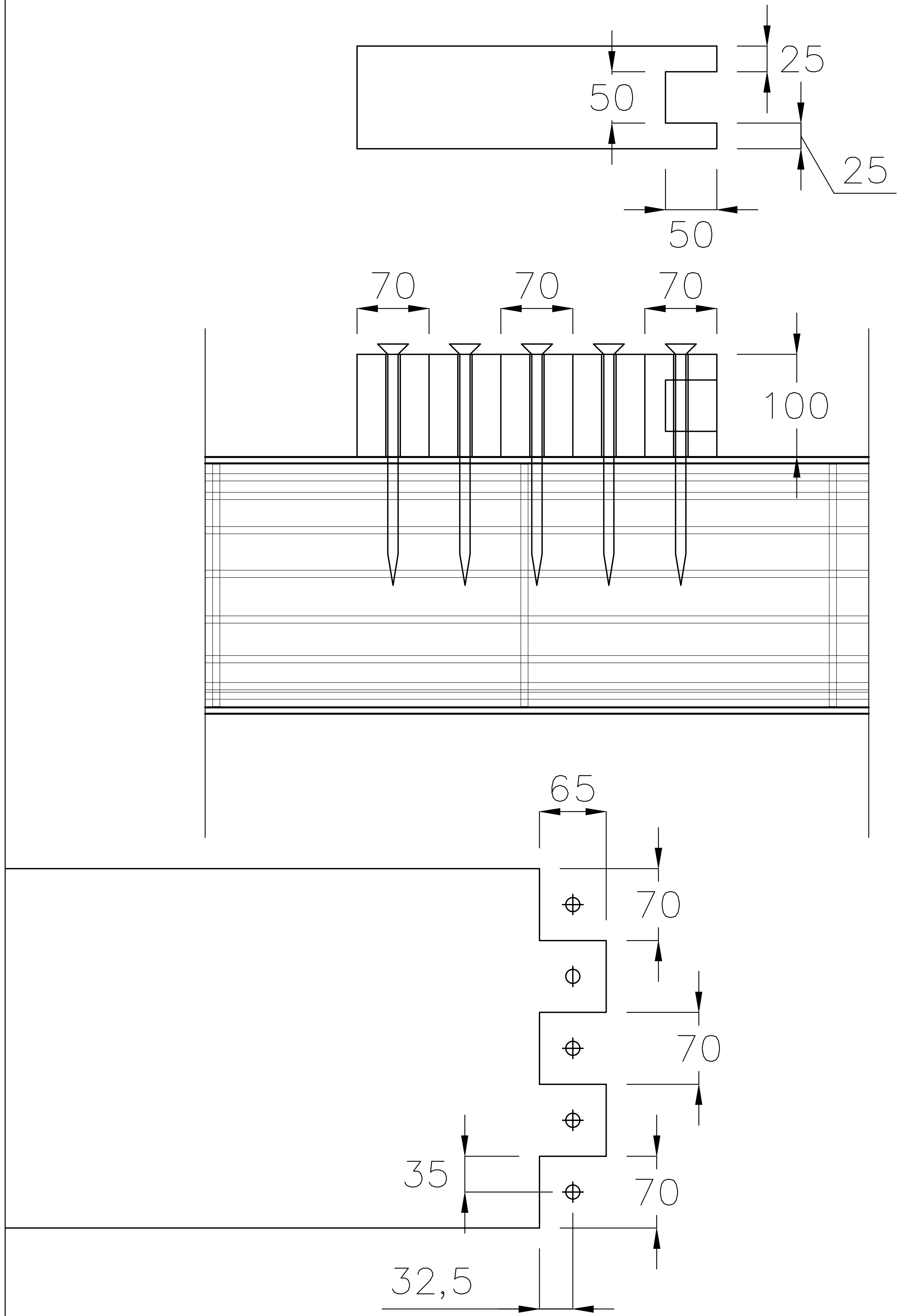

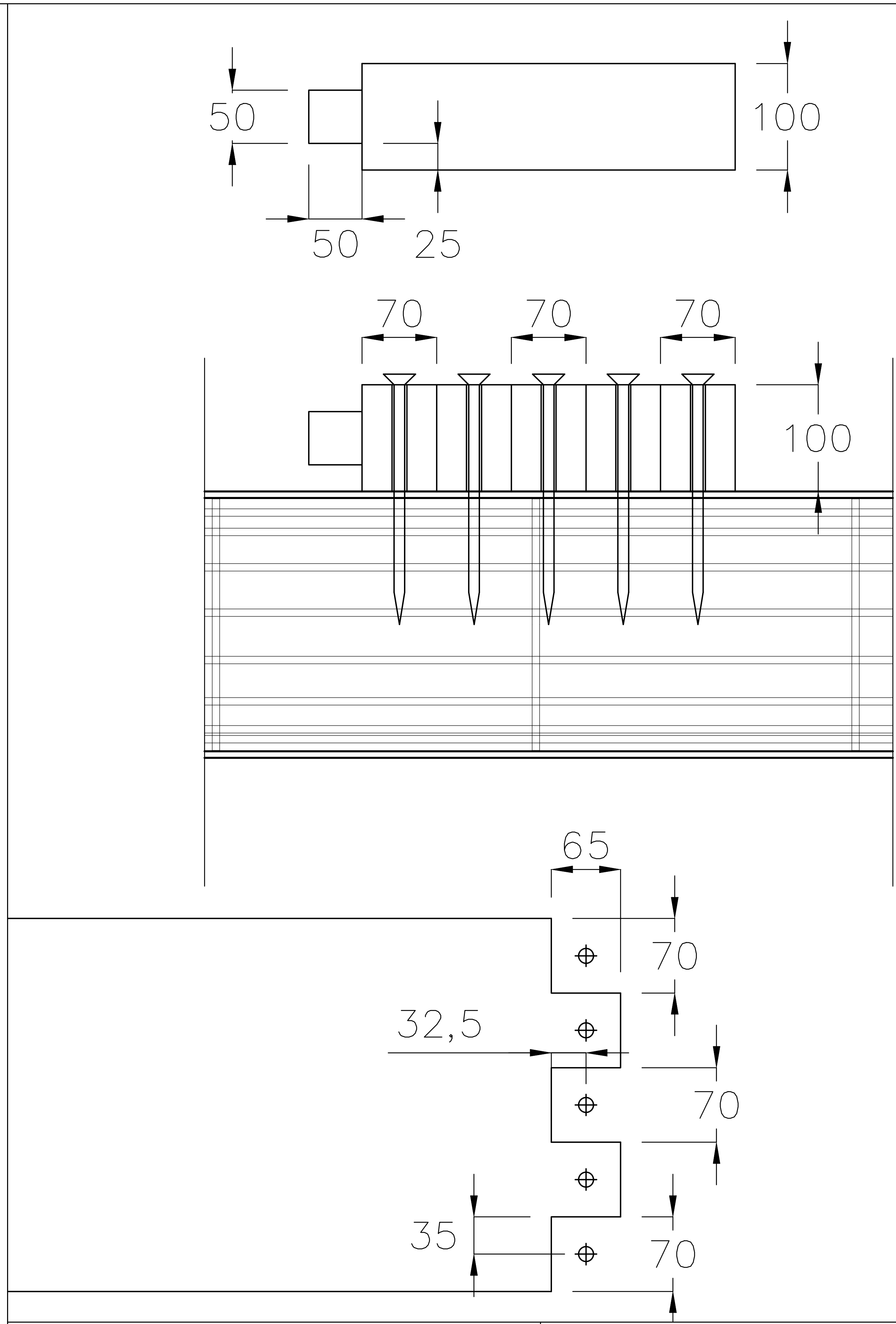

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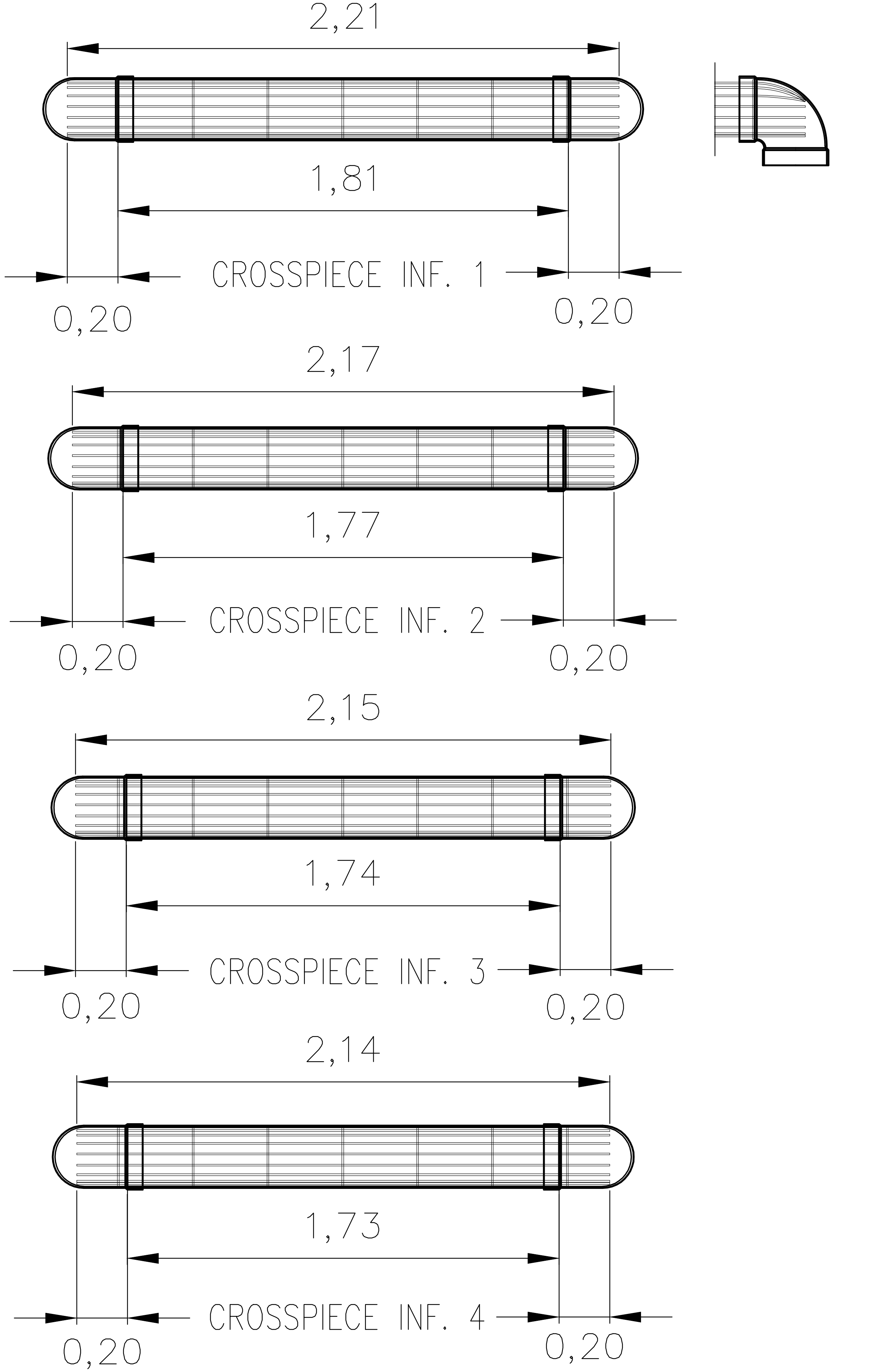

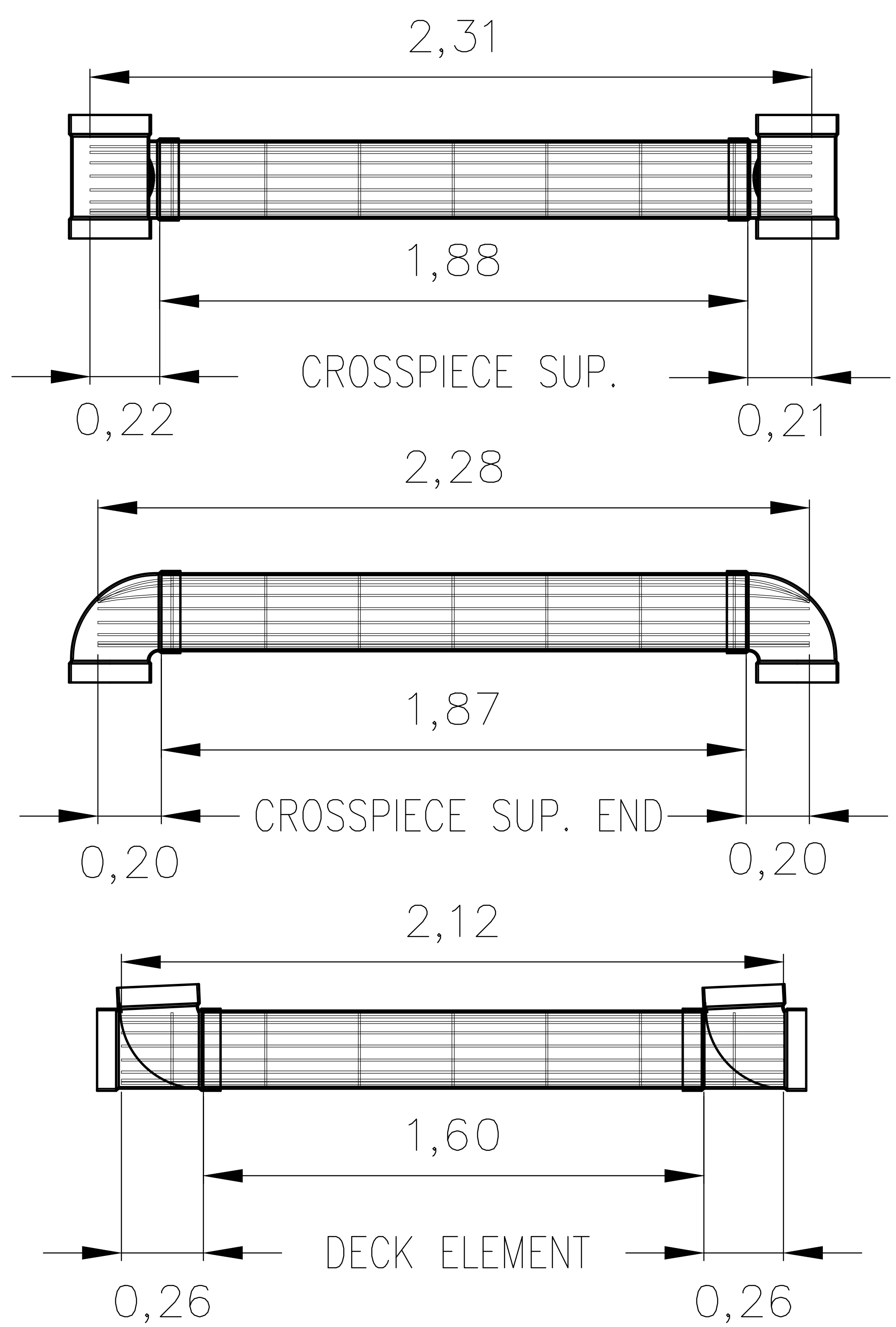

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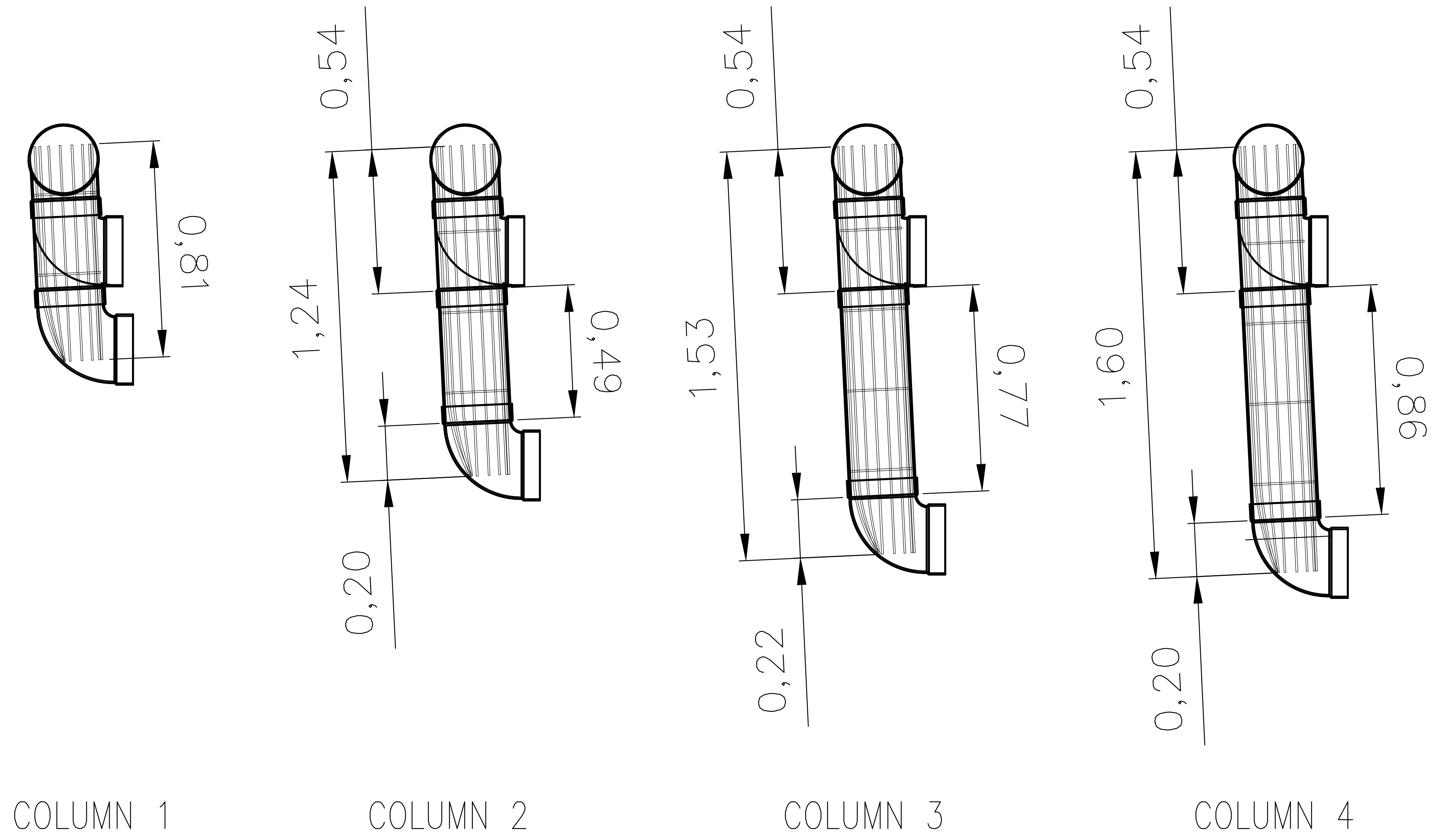

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