Master Thesis

The elevated metro structure in concrete, UHPC and composite

Literature and preliminary study

Rotterdam, October 2010

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Figure front page: the Bangkok Mass Transit System [i23]

Preface

This report presents the results of my literature and preliminary study of my graduation thesis. Together with my design study this forms my Master graduation thesis. This project was performed to obtain my Masters degree in Civil Engineering at Delft University of Technology. The project was carried out at the engineering office of Rotterdam Public Works in cooperation with the Faculty Civil Engineering & Geosciences, Department of Design & Construction.

The graduation committee consisted of the following members:

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I would like to thank the engineering office of Rotterdam Public Works for providing me with a pleasant workplace at their office. Furthermore my gratitude goes to my colleagues for the enjoyable and relaxed atmosphere during my graduation time. Finally I would like to thank my graduation committee for their support and advice, and especially Kees Blom for his enthusiasm and personal guidance.

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Summary

To keep cities and metropolises accessible it is seen more and more that the infrastructure is elevated high above the ground. An elevated metro system has the advantage that it is cheaper than an underground metro system and the construction time is much shorter. The physical barrier caused by the realisation of an elevated system is also less than that of a metro system at ground level (only columns). One major disadvantage is the visual barrier of an elevated metro system. This is especially the case for a practical elevation of about 5 metres. The realisation of such elevated lines often causes resistance from residents. There is however a trend to increase the elevation even more, up to a height of about 10 to 12 metres. This is applied in some large cities/metropolises and seems to cause less visual hindrance as it creates a more open and lighter space below the structure. At the same time it can, if well designed, serve as an attractive landmark that gives the city a unique appearance.

In the future, Rotterdam wants to extent its existing metro system. An elevated metro system high above the city is one of the possible concepts. The engineering office of Rotterdam Public Works is interested in this concept and moreover in whether there can be gained profit on the elevated metro structure by applying Ultra High Performance Concrete or Fibre Reinforced Polymers instead of conventional concrete. The objective is to determine the dimensions and normative structural verifications of the elevated metro structure when this is made of conventional concrete, Ultra High Performance Concrete or Fibre Reinforced Polymers and to compare these designs with each other. The graduation thesis exists of two parts: the literature and preliminary study and the design study. The design study concerns the structural design and analysis of the elevated metro structure and results in three designs made of respectively conventional concrete, Ultra High Performance Concrete (UHPC) and Fibre Reinforced Polymers (FRP). The literature and preliminary study gives information about important aspects of elevated metro systems, UHPC and FRP and has as major objective to determine the height and span of the elevated railway for the application of an elevated metro system in Rotterdam.

Reference projects show that the alignment of an elevated metro system within a city follows the street pattern as much as possible. From a social point of view, the stations are made very transparent. The stations often consist of three levels: ground level with the access points; first level with the stations concourse; and the second level with the station platform(s). Furthermore, reference projects show that it is possible to create elevated metro systems that have a small environmental impact. The span-to-height ratio of elevated metro lines ranges between 2 to 4. For the determination of the bridge type, it is important to take into account the material and construction prices, which can differ from country to country.

The possible means for vertical transportation inside an elevated metro station are stairs, escalators and elevators. The use of moving walkways is not efficient enough. The stations will always have stairs, as this is required in emergencies. Also at least one elevator is necessary to make the station accessible for disabled persons. The choice between stairs, escalators or elevators as major means of vertical transportation depends on the height of the elevated metro station. For very small elevations stairs are chosen. When the height becomes larger and terraces for the stairs are necessary (rise of more than 4 metres), escalators are the best option. Elevators are chosen as major means of transportation if the elevation exceeds 30 metres.

The structure of an elevated railway is similar to that of a bridge. There are many types of bridges all with their own characteristics, span range and possible construction methods. Important for a metro line is the ability to follow a curved alignment. A curved alignment can be created by building several shorter straight spans or by using horizontally curved girders. The latter creates a far more uniform and aesthetical structure. The curvature however limits the maximum span length. Furthermore, it is important to take into account the maintenance and replacement of the bridge in the design phase.

A suitable height of an elevated metro system in Rotterdam ranges between 9 and 15 metres. The height of 9 metres is chosen, as people within an average building of 9 metres high can look straight out of the window without seeing the elevated railway. The height of 15 metres follows from a maximum span of 45 metres and a span-to-height ratio of 3 to create a more aesthetical appearance.

The reason for a maximum span of 45 metres is twofold: Firstly, with this span length it is expected that the metro alignment can follow the cities street pattern and fits into the proportions of the city. Secondly, this is seen as the most economical span as it can be built with in-situ concrete, precast concrete and steel girders. Rotterdam is however not just a city but wants to distinguish itself from other cities and as an elevation of 12 metres becomes more common an elevated metro system in Rotterdam should have an elevation of 15 metres. A higher elevation creates also a more open and lighter area underneath the structure. Moreover, this is more challenging for further elaboration in the design study of the graduation thesis. If the elaboration of the elevated railway with a span of 45 metres turns out to be an appropriate structural design it is still possible to diminish the height.

Ultra High Performance Concrete (UHPC) is a result of the search for a concrete with a higher strength. The strength classes of UHPC range between C90/105 and C200/230. The creation of UHPC is made possible by changing the design of the concrete mix by: improving the homogeneity and the microstructure, increasing the package density, adding steel fibres and reducing the water-cement ratio. The material has a high durability and can result in more slender structures. The costs are however high compared with conventional concrete. Furthermore, the mix design of UHPC is complex and deserves special attention. It is assumed to be the best to utilize precast UHPC elements instead of in-situ UHPC. For the design of the elevated railway made from UHPC in the design study a thesis is used [2].

Fibre Reinforced Polymers (FRP) is a composite material. FRP consists of load-bearing fibres and a polymer resin matrix in which they are embedded. Whereas the fibres exercise the actual load-bearing function, the polymer matrix essentially has four functions:

- Fixing the fibres in the desired geometrical arrangement
- Transferring the forces to the fibres
- Preventing buckling of the fibres under compression actions
- Protecting the fibres from humidity etc.

There is a wide range of FRP producible which has resulted in few standard composites and standard codes. FRP has a very high strength at low weight and by adding additives it can be mixed for many suitable applications. And as there is a wide range of FRP producible there are also many manufacturing processes. Points of interest are the possibility of delamination and the stiffness of the bridge. The cost for FRP is relatively high. Sandwich construction is commonly used with composites to increase structural efficiency, with the FRP forming the outer skins and bonded to a variety of core materials. For the design of the elevated railway made from FRP in the design study a thesis is used[17].

1. Introduction

1.1 Metro systems

A metro system is an electric passenger railway in an urban area. Characteristics of a metro system are the high capacity and frequency at which it transports people and the grade separation from other traffic. The grade separation allows the metro to move freely, with fewer interruptions and at higher overall speeds. Furthermore, there are fewer conflicts between traffic movements, which reduce the number of accidents, making it a safer way to travel. Grade separation for metro systems is realised by placing it in underground tunnels, elevated above street level or grade separated at ground level. Often a metro system is a combination of these three options.

Beside the traditional metro using electric multiple units on rails, nowadays one can find also some systems using magnetic levitation or monorails. By changing the capacity of the trains, the frequency and the distance between the stations, variations on traditional metros like people movers and light metros have appeared. At the same time, technological improvements have allowed new driverless lines and systems. With all these variations in metro systems it is sometimes difficult to determine to what type a system belongs. Despite all these variations, they have in common that they are executed more and more as elevated railways in dense urban areas.

1.2 Problem description

Building underground metro systems is very expensive and takes a lot of time to realise. Besides, it is often a risky operation in urban areas. In areas with high land prices and dense land use, this option may however be the only economic route for mass transportation. The construction of ground level metro lines is the cheapest of the three options, as long as the land values are low. Since ground level metro lines create a physical barrier that hinders the flow of people and vehicles it is mostly used outside dense urban areas. Elevated railways are a cheap and easy way to build an exclusive metro line without digging expensive tunnels or creating physical barriers. Considering this from a practical and economical point of view, an elevated metro system is often the most suitable solution of the three options.

In some metropolises the infrastructure is elevated up to a large height above the city. In the Netherlands this concept can also be found, but often concerns a practical elevation of about 5 metres. This elevation allows car traffic to pass underneath. Due to the limited height, this is however often seen as a psychological barrier between two areas. By increasing the elevation as is applied in some metropolises this psychological barrier decreases. This makes the concept more attractive as alternative for the extension of the public transport. Moreover, as mentioned above an elevated metro system has the advantages that it costs less and takes less time to construct compared with an underground metro system and does not create a physical barrier. With a higher elevated metro system it is thus possible to create an even more attractive alternative as it is also accepted more from a social point of view. This all makes this concept truly worth to take into consideration as option for mass transportation by metros.

In the future, Rotterdam wants to extent its existing metro system. An elevated metro system high above the city is one of the possible concepts. The engineering office of Rotterdam Public Works is interested in this concept and moreover in whether there can be gained profit on the elevated metro structure by applying Ultra High Performance Concrete or Fibre Reinforced Polymers instead of conventional concrete. More specific, they would like to know if an elevated metro structure made of Ultra High Performance Concrete or Fibre Reinforced Polymers results in different structural dimensions. Besides, the question is what the normative structural verifications are when these materials are applied to an elevated metro structure.

Notice that the title of this thesis contains the term “composite”. The term “composite” covers a wide range of material combinations. However, in this thesis “Fibre Reinforced Polymers” is meant with the term “composite”.

1.3 Problem definition

What are the dimensions of the elevated metro structure made of conventional concrete, Ultra High Performance Concrete or Fibre Reinforced Polymers and what are the normative structural verifications in these cases?

1.4 Objective

Determine the dimensions and normative structural verifications of the elevated metro structure made of conventional concrete, Ultra High Performance Concrete or Fibre Reinforced Polymers and compare these designs with each other. The height and span of the structure should fit in the city of Rotterdam.

1.5 Work approach

The graduation thesis exists of two parts: the literature and preliminary study and the design study. The literature and preliminary study concerns the first part of the thesis and treats among other things: already existing elevated metro systems and the functional design of an elevated metro system in Rotterdam. This study gives information about important aspects of elevated metro systems and has as major objective to determine the height and span of the elevated railway for the application of an elevated metro system in Rotterdam. These dimensions together with the other information of the literature and preliminary study are taken into account in the design study. The design study concerns the final and major part of this thesis and treats the structural design of the elevated metro structure. Different concepts are analysed for the elevated railway structure made of conventional concrete and Ultra High Performance Concrete (UHPC) and the best concept is further elaborated. Besides, a global design for the elevated railway structure made of Fibre Reinforced Polymers (FRP) is presented. The three designs are finally compared with each other which give a clear view on the differences in dimensions and normative structural verifications between the application of conventional concrete, Ultra High Performance Concrete and Fibre Reinforced Polymers.

This report concerns the literature and preliminary study and treats six aspects related to elevated metro systems. First of all, existing reference projects are examined in chapter 2 to give a clear insight into the application of elevated metro systems. The examined projects are: the Vancouver SkyTrain, the Bangkok Mass Transit System and the Nesselandelijn. The second aspect is vertical transportation and is described in chapter 3. This aspect is examined as it is important to create an accessible mass transit system. Chapter 4 treats the subject bridges as the structure of an elevated railway is similar to that of a bridge. In this chapter different bridge types all with their own characteristics, span range and possible construction methods are presented as well as maintenance aspects. Taking the information from the previous chapters into account, chapter 5 discusses the application of an elevated metro system in Rotterdam. The suitable span and height of the elevated railway is decided in this chapter. As in the design study the materials UHPC and FRP are applied, these materials are also briefly discussed in this report. UHPC is treated in chapter 6 and FRP in chapter 7. The literature and preliminary study ends with the conclusions considering the application of an elevated metro system in Rotterdam, recommendations and continuation of the thesis.

References to literature in the text are indicated with [X], where X is a number which refers to the reference list at the end of this report. References to internet pages are indicated with [iX].

2. Reference projects

2.1 Vancouver SkyTrain

References: [i2] [i7] [i10] [i14] [i15] [i19] [i24] [i27] [i28] [i36] [i40] [i43] [i44]

The Vancouver SkyTrain is an urban rapid transit system in metropolitan Vancouver, British Columbia, Canada (see Figure 1 and Figure 2). It uses fully automated trains running mostly on elevated tracks (hence the name). It is the world's longest automated light rapid transit system and uses the longest mass transit-only bridge, the SkyBridge, to cross the Fraser River. The Vancouver SkyTrain has three lines and carries an average of 350.000 passengers per day (2009). A third rail electrifies the system and it has a standard gauge of 1435 mm.

Figure 1: Brentwood station

Figure 2: SkyTrain and skyline of Vancouver

2.1.1 Alignment

The Expo (dark blue) and Millennium (yellow) SkyTrain Lines connect downtown Vancouver with the cities of Burnaby, New Westminster and Surrey. The Canada Line (light blue) connects downtown Vancouver to the Vancouver International Airport (YVR) and the city of Richmond (see Figure 3). The system is 68.7 km long and features a total of 48 stations. Waterfront Station in Downtown Vancouver is the only connection for all the SkyTrain lines, and also connects with the West Coast Express and SeaBus. Vancouver City Centre Station, however, is within a three minute indoor walk from Granville Station, making it an unofficial connection between the three SkyTrain lines. The Millennium Line shares tracks with the Expo Line from Waterfront Station to Columbia Station in New Westminster, then continues along its own route through North Burnaby and East Vancouver, ending at Vancouver Community College (VCC-Clark Station) in Vancouver. Although most of the system is elevated, SkyTrain runs at or below grade through Downtown Vancouver, for half of the Canada Line's length, and for short stretches in Burnaby and New Westminster.

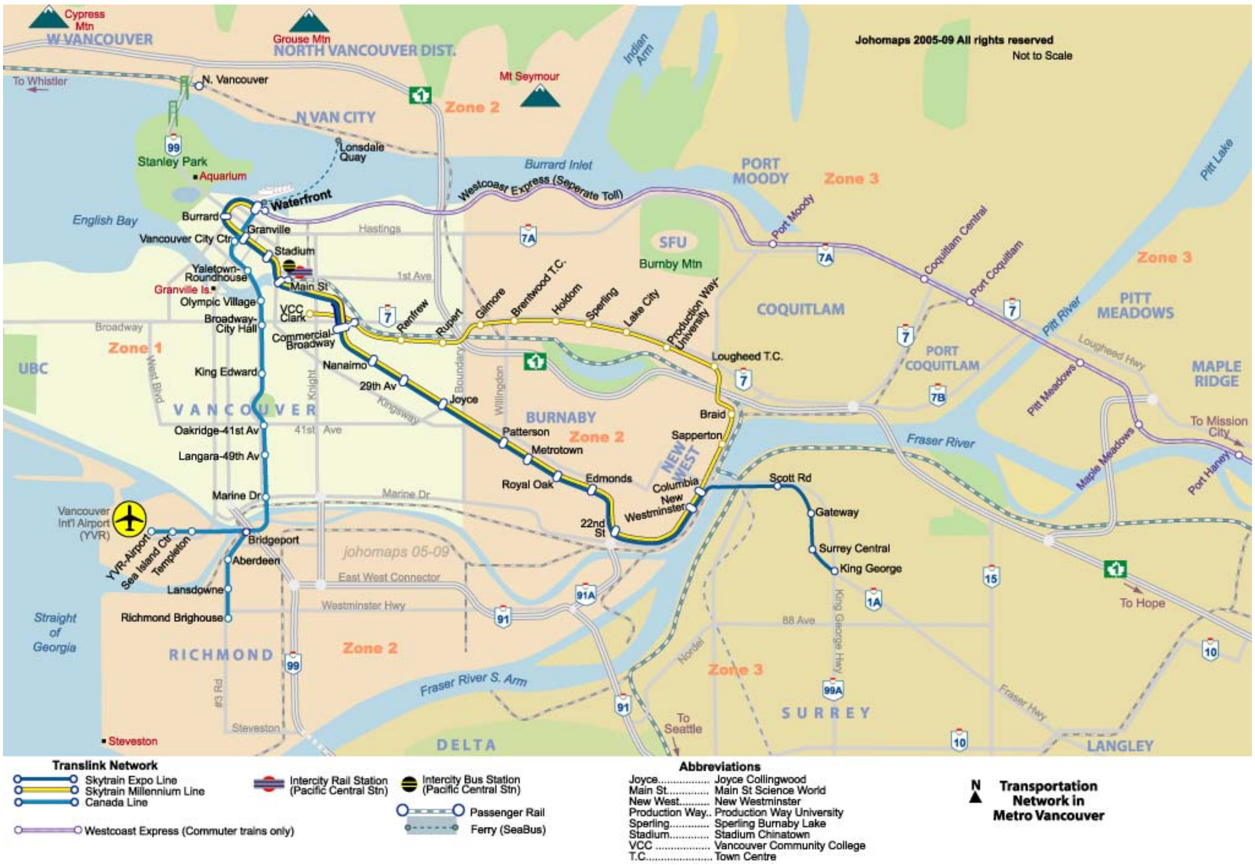

Figure 3: Transportation network in Metropolis Vancouver

2.1.2 Stations

The Expo and Millennium Line station platforms are 80 m long and the Canada Line station platforms have a maximum length of 50 metres. This difference in platform length is because the Canada Line uses a different rolling stock than the other two lines. The elevated stations have precast concrete decks. The average station distance is 730 m in the city centre area and 1750 m in other areas. All stations now have elevators, after Granville was retrofitted with one in 2006. All the Canada Line stations have an up-escalator and elevator, but only the three terminal stations (Waterfront, Broadway City Hall and Bridgeport station) have down-escalators. SkyTrain stations have been specifically designed to make customers feel safe and secure. Clear sight lines allow people to see and be seen (see Figure 4). Because the SkyTrain system is not elevated along the whole line but also runs at street level and underground, there is not a specific design for all the stations. Each station along the Canada Line is slightly different in appearance, and designed to blend in with the surrounding neighbourhood. However, for the elevated stations it turns out that most elevated stations have three levels (see Figure 5):

- Street level: the entry point for the station.
- First level: The concourse level.
- Second level: the platform level.

Station platforms, entrances, elevators, escalators and corridors are monitored by Closed Circuit Television Cameras. On average, there are approximately 23 cameras per station. SkyTrain Attendants (STAs) are present to provide first aid, direction and customer service, inspect fares, monitor train faults, and operate the trains manually if necessary.

Figure 4: Gilmore station

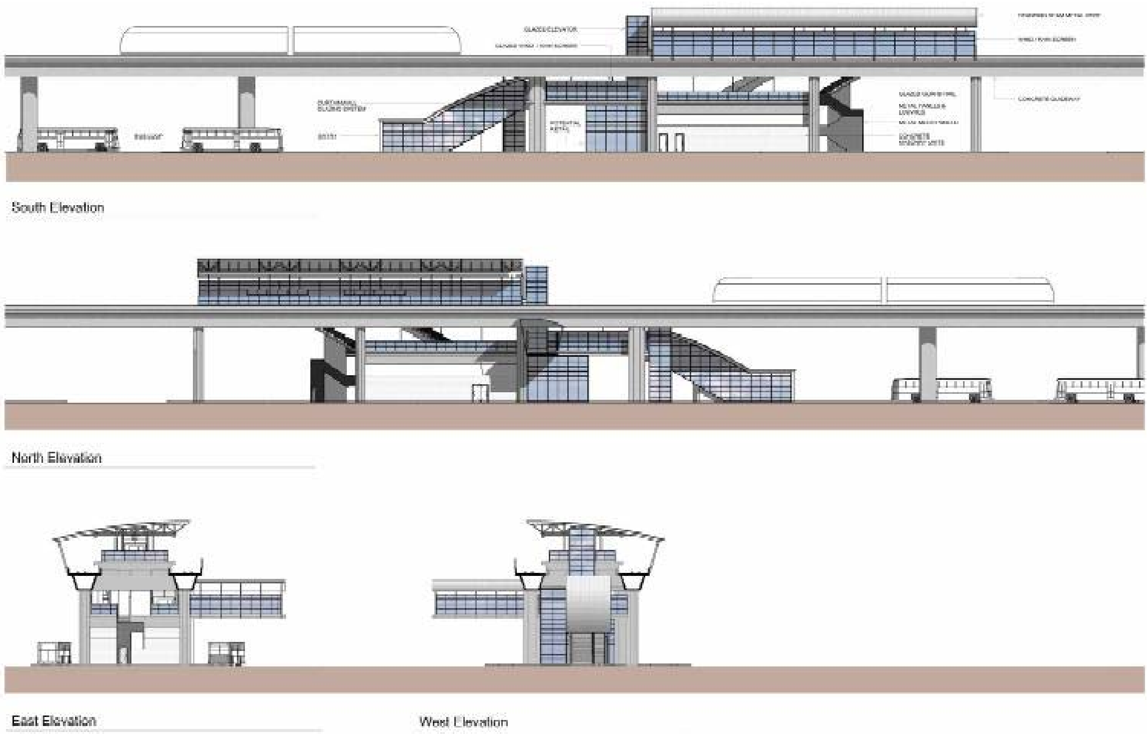

Figure 5: Bridgeport station, notice the three station levels and the overhead pedestrian bridge

2.1.3 Track construction

The elevated part of the SkyTrain in Vancouver is a segmental bridge supported on columns. The columns are cast in-situ (see Figure 6) and are about 12 metres high. The railway girders consist of precast concrete segmental box girders and are post tensioned (see Figure 7 and Figure 8). The first line, the Expo line, was built using cranes to lift the precast segments. These cranes were so large and heavy that they sometimes damaged the streets they worked on. In order to minimize the traffic disruption in the neighbourhood during construction, launching trusses were used for the erection of the railway girders of the Millennium and Canada line (see Figure 9 and Figure 10). The box girders are about 37metres long (Millennium Line) and support single or double track (see Figure 11). Most of the system uses double track and the whole is grade separated from other modes of transport.

The foundations that hold the columns were created using drilled pier technology[1]. In areas where it was appropriate, spread footing foundations were used instead of drilled piers. The construction of the Millennium and Canada Line was carried out under strict rules to protect the environment. Monitors worked on all job sites to ensure protective measures were effective and properly implemented. Where construction took place near streams, measures were taken to ensure that no soil or other contamination occurred. All areas that were disturbed during construction were restored. Some areas were even improved as bird, fish and wildlife habitat.

2.1.4 Controversy

When the results of the bidding process indicated that an elevated option in Richmond for the Canada line was the winning bid, Richmond council engaged in some last minute opposition to the line and refused to give the green light. Objections to the elevated line included its visual impact, and the impact and cost of any extensions into Richmond. The line would have varied impact on businesses along No. 3 Road. It was said that an at-grade option would cost an extra $90 million due to the need to purchase cars that could accommodate drivers. In order to meet travel time criteria it was also argued that several intersections would need to be closed. It was also said that an at-grade option would require a large wall to protect the track along No. 3 Road.

In November 2004, a survey of 11,750 people was conducted to determine if people in Richmond supported an elevated or at-grade service in Richmond. 58 Percent of the respondents favoured an elevated option. Even after the survey, however, another option was brought forward. On November 22, 2004, Richmond council considered whether an elevated railway along No. 3 Road in Richmond was appropriate. If an at-grade service was not feasible, the council had instructed the staff to look into the possibility of relocating the elevated railway further west along Minoru Boulevard. In response, residents along Minoru Boulevard presented a petition containing 666 signatures opposing the Minoru alignment. In the petition they indicated that if the governance of the project was not prepared to construct an at-grade system on No. 3 Road, then the project should be abandoned in favour of bus service on No. 3 Road.

When further surveys and public consultation conducted by city staff in December indicated that residents did not support the realignment along Minoru Boulevard, the council was left to either turn down the development or support the best and final offer. They chose to go ahead with the project. As a final compromise, part of the elevated track in Richmond was single track to reduce visual impact.

For more information about the Vancouver SkyTrain reference is made to Appendix 1: Vancouver SkyTrain.

[1] Steel casings are vibrated into the ground, the earth is then removed from the centre of the casing, a reinforcing steel cage is lowered into the casing, and concrete is placed.

Figure 6: The columns cast-in-situ

Figure 7: External prestressing tendons in the box girders

Figure 8: Post-tensioning of a bundle with strands

Figure 9: Construction of the box girders using a launching truss

Figure 10: Construction of the girders using a launching truss

Figure 11: A single track railway girder

2.2 Bangkok Mass Transit System

References: [i1] [i5] [i12] [i18] [i28] [i39] [i45]

The Bangkok Mass Transit System, commonly known as the BTS SkyTrain, is an elevated metro system in Bangkok, Thailand (see Figure 12and Figure 13). The BTS SkyTrain operates as a high-capacity mass transit system using double track running in opposite directions. The trains consist of three passenger cars and are electrified via a third rail. Each train has a combined capacity to carry up to 1000 passengers. The BTS SkyTrain currently records over 450,000 passenger-trips per working day (June 30th, 2009). Unlike some other elevated light rail systems such as the Vancouver SkyTrain, the trains are manually driven.

Figure 12: SkyTrain and skyline of Bangkok

Figure 13: BTS SkyTrain high above the streets

2.2.1 Alignment

The system consists of twenty-five stations along two lines: the Sukhumvit line running northwards and eastwards, terminating at Mo Chit and On Nut, and the Silom line which terminates at the National Stadium and Wongwian Yai (see Figure 14). The lines interchange at Siam Station and have a combined route distance of 55 km. On metro maps the Sukhumvit line and the Silom line are represented by the colour light green and respectively dark green. The two SkyTrain lines are built along the roads of the city and have different interchanges with the underground metro system (Bangkok MRTA, blue line) and the railway network (State Railway of Thailand, SRT) (see Figure 14).

Figure 14: Map of the two BTS SkyTrain lines

2.2.2 Stations

Most of the BTS station infrastructure has been designed to be above ground in order to avoid cluttering existing street-level facilities and contributing to further traffic congestion. Most of the stations have a single-column support structure and each station is 150 metres in length. There are two types of stations:

1. Side Platform Stations (see Figure 15) – Most BTS stations have been designed with two platforms at each side of the station, with two train tracks running through the centre. This design works well with a single-column support structure.
2. Centre Platform Stations – More complex in terms of construction and serving a higher passenger capacity. This type of station has a large platform in the centre with tracks at each side. BTS uses this design only at Siam station to facilitate cross-platform interchange between the two lines.

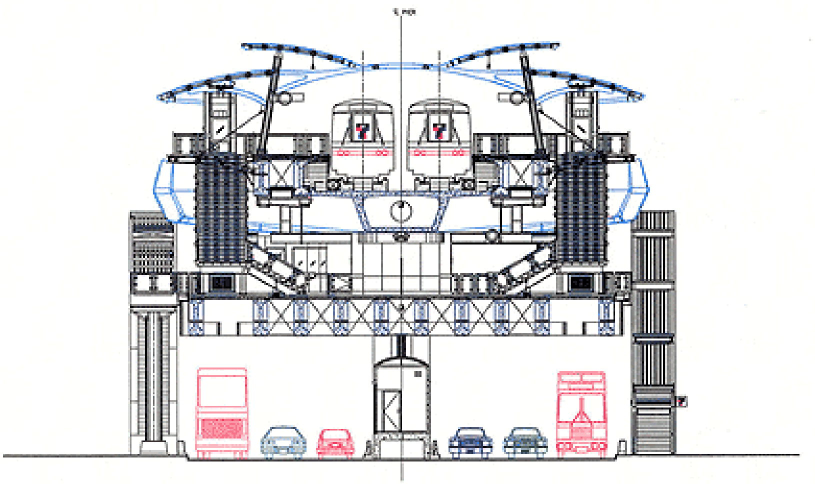

Figure 15: Cross-section of a side platform station

Each station has three levels:

1. The Street Level is the entry point to each station. Stairways, escalators and elevators (at selected stations) lead the passengers to the concourse. The Street Level is also used to store equipment such as generators, fuel tanks, water tanks and water pumps.
2. The Concourse Level is located above the Street Level and serves as the entry point to the platform. Several main stations have ‘Skybridges’, overhead pedestrian walkways that conveniently connect the concourse directly to the neighbouring shopping and commercial centres (see Figure 16). The concourse is divided into the public area for those who have not yet entered the BTS system through the ticket gate and the internal station or paid area, for all passengers who have entered the system. The public area contains the Automatic Ticket Machine, the staffed BTS Station Ticket Office and the ticket gates. This level, together with the ‘Skybridges’ also offers facilities such as small shops, cafes, banking services and ATM machines. The internal station area leads from the ticket gates to the platform using stairways and escalators. There are additional facilities in this section, including newsstands, small shops and ATM services, as well as restricted areas, accessible only to BTS staff.
3. The Platform is the highest level of each station. All station platforms offer elegant sheltering and are located on one level with the exception of Siam interchange (transfer) station, which has two platform levels to facilitate passenger transfer between the Silom and Sukhumvit train lines.

Each station is equipped with a closed-circuit TV system and a central Control Panel to regulate station escalators and elevator. Furthermore police and security guards are stationed at the stations at all time.

Figure 16: A side platform station with ‘Skybridges’ (overhead pedestrian walkways) above the roads

2.2.3 Track construction

The elevated railway structure mostly consists of a 9-metres wide railway supporting double track, fixed directly to concrete plinths. Only at the interchange station Siam, the tracks split up, resulting in a smaller viaduct supporting a single track (see Figure 17). The railway girders are precast concrete segmental box girders and were erected in place by launching trusses. External prestressing tendons are installed to connect the segments (see Figure 18). The elevated track has a single-column support and where this was not possible, portal frame structures are applied (see Figure 12). The track is elevated 12 metres above street level. The concrete columns are cast in-situ and the spans of the box girders are about 30 to 35 metres (see Figure 19). The foundation consists of drilled piers which go to a depth of 50 metres. At some places, barrette piles are applied as foundation (see Figure 20). At some sections a pedestrian walkway is integrated with the elevated metro system (see Figure 21).

Figure 17: Single-track viaducts near Siam station

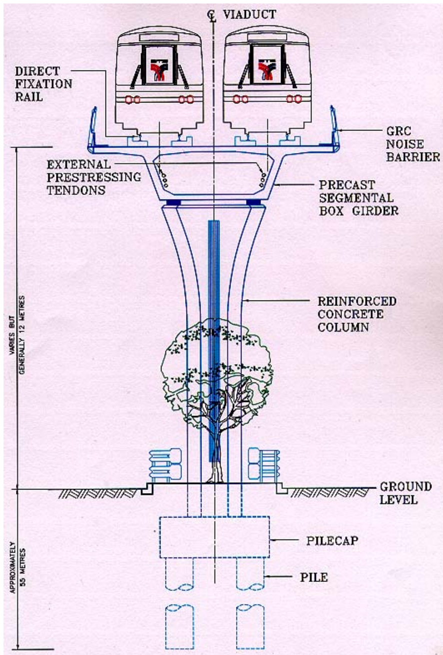

Figure 18: Cross-section of the elevated metro structure

Figure 19: Cast in-situ columns with box girder segment

Figure 20: Excavation using a grab for the construction of a barrette pile

Figure 21: Supports for a pedestrian walkway

For more information about the BTS SkyTrain reference is made to Appendix 2: Bangkok Mass Transit System.

2.3 Nesselandelijn

References: [11] [12] [13] [14] [15] [16] [i13] [i28] [i29] [i31]

The Nesselandelijn is part of the Rotterdam Metro network and runs mainly on elevated tracks (see Figure 22). It is the extension of the Calandlijn from the former end station 'De Tochten' in Zevenkamp towards Nesselande. The metros are manually driven and the railway has a standard gauge of 1435 mm. The Nesselandelijn uses double track running in opposite directions and a third rail electrifies the metros. The metro units have a length of about 30 metres and a maximum capacity of 260 passengers. The maximum length of a combined metro can consist of four metro units, which means a length of 120 metres. The Nesselandelijn is about 1500 metres long and has no at-grade crossings, which enables the metro to drive faster and safer. The construction of the railway and the station of the Nesselandelijn cost about 105.5 million Euros.

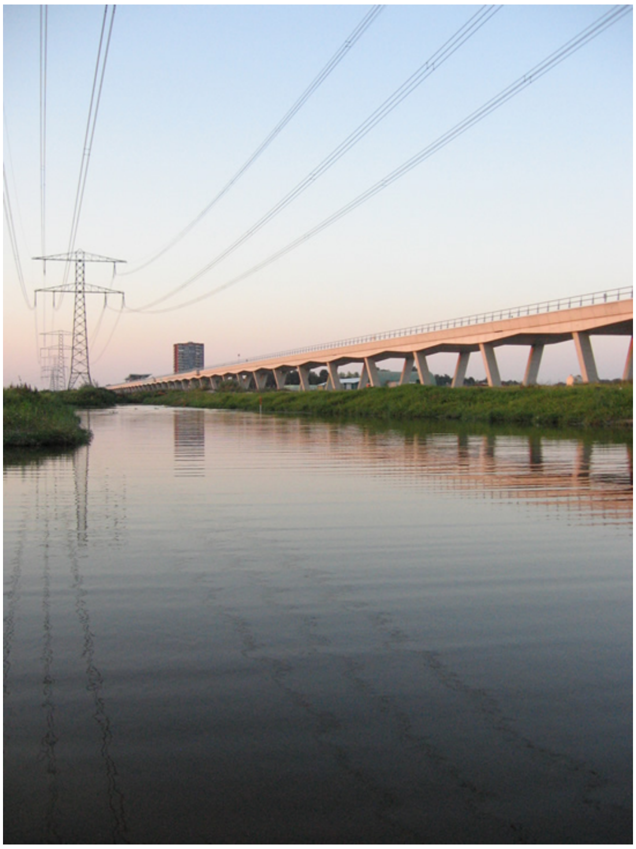

Figure 22: Nesselandelijn under and parallel with high-voltage cables

2.3.1 History

The Nesselandelijn is in use since august 2005. The building of the Nesselandelijn started officially on May 2003. Nesselande is a VINEX location and has therefore made a quick development (many dwellings, shops and other facilities where built within a short time period). In order to keep Nesselande accessible and the car traffic controllable it was decided to extend the metro line towards the centre of Nesselande. After the realisation of the Nesselandelijn, the surrounding area was developed. This was probably decided to prevent troubles with the residents near the line. Many people were very unhappy about the metro driving on an elevated railway. Even today many people find it an unlucky choice made by the municipality. Fact is however that it is cheaper than a tunnel and faster and safer than a metro line at street level.

2.3.2 Alignment

The Nesselandelijn starts from station De Tochten at ground level. A piled concrete slab supports the first 368 metres of track. Near the end, the slab has an inclination where the viaduct is connected. The elevated part consists of a 683-metres double track viaduct and two 469-metres single track viaducts. The total system length of the Nesselandelijn is thus 1520 metres. Near metro station Nesselande the Metro runs on single track viaducts. The metro line has a north-south position after it passes metro station De Tochten and has crossed an underground gas pipe and overhead high-voltage cables (see Figure 23). After the curve, it runs under and parallel with the high-voltage cables (see Figure 22).

Figure 23: Map of the Nesselandlijn

2.3.3 Station

Metro station Nesselande is designed by Hans Moor and is made of a lot of steel and glass (see Figure 24). It has a modern and dynamic appearance. The station has an island platform with a length of 93 metres but in the future it can be extended to a length of 125 metres. This means that the maximum length for a combined metro consists of three metro units. An island platform has the advantage that facilities like an escalator and elevator are needed for just one platform and not for two platforms, which is the case for a side platform station. Within the scope of social security an island platform also scores better. The station has two levels: the concourse at ground level and the platform above. There are two entrances/exits, one of them with an escalator. Both entrances/exits have a stair and one elevator can be found in the station. The station is made very transparent for safety reasons and during its exploitation hours the station is manned by RET employees. There are also cameras which observe the station and its surroundings.

Figure 24: Metro station Nesselande

2.3.4 Track construction

The viaduct of the Nesselandelijn is a trough bridge and is cast-in-situ. A trough bridge consists of two parallel beams with the floor in between (see Figure 25). Both supporting beams also serve as cable duct, emergency walkway and acoustic shielding. By integration of these functions the viaduct can be made very slender. The column distance is 20 metres. A smaller span would however not reduce the depth of the beams as the emergency walkways should still have the same height. Besides, a smaller span would increase the number of columns what also increases the visual hindrance of the viaduct. The tracks are fixed on the intervening floor. The elevated railway is cast in sections of 60 metres and is reinforced with steel bars (no prestressing). It is supported by three column rows and has at both ends a cantilever (16 m + 20 m + 20 m + 4 m = 60 m). The floor thickness and supporting beam depth is not constant and tapers towards the middle of the span (see Figure 26). This reduces the own weight of the railway and makes it possible to span 20 metres instead of 12 metres. It also creates a more slender and aesthetical structure. It was unwanted to use cross-girders as support for the viaducts and therefore the supporting beams were supported by columns. Vertical columns under a double track viaduct lead to a large space under the railway and between the columns. With two single track viaducts this would lead to four columns on a row close to each other. Therefore it was chosen to place the columns sloped, the V-column (see Figure 27). This reduces the required space at the surface and gives a more spatially perception. The V-columns are supported by a pile cap with pile foundation. For the construction of the viaduct they made use of temporary semi mechanical falsework which was supported at the pile caps. At that time there were some large infrastructural projects on the market which forced up the prices. There was a great demand for precast concrete which made it expensive. It was decided to build the structure with cast in-situ concrete to be independent of precast concrete and be able to involve more contractors with the realization, all aimed at saving costs.

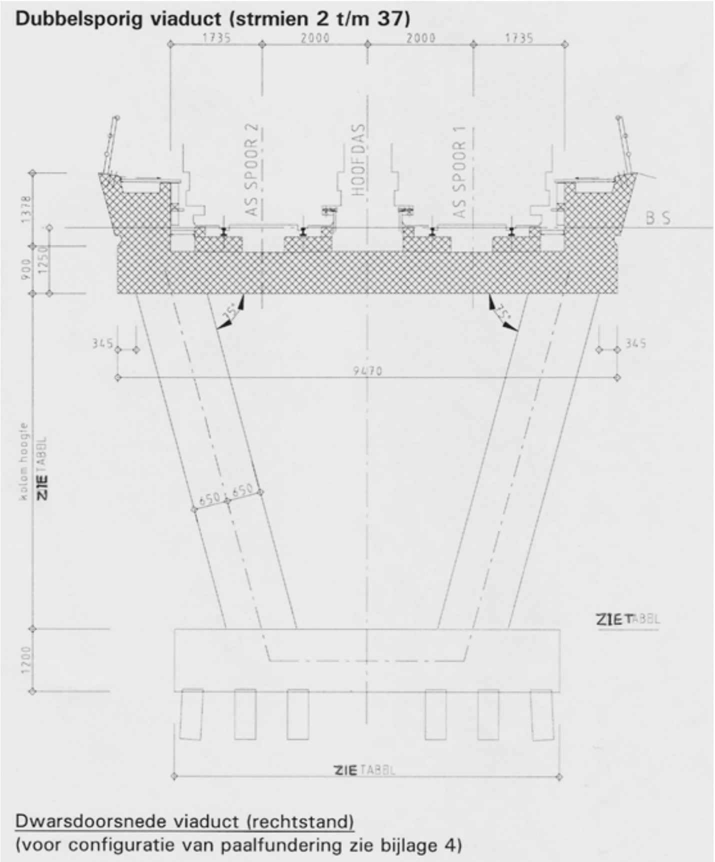

Figure 25: Cross-section of the double track viaduct

Figure 26: The tapered railway structure supported by a falsework

Figure 27: Reinforcement of the V-columns

For more elevated metro systems reference is made to Appendix 3: More elevated metro systems.

2.4 Analysis reference projects

This reference research shows that there are quite some high elevated metro systems in the world. In general, reference projects show that the alignment of an elevated metro system within a city follows the street pattern as much as possible. Otherwise it is better to build the metro system first and thereafter develop the surrounding area to prevent trouble with the residents. It seems that an elevated metro system with an elevation of about 10 to 12 metres is more accepted from a social point of view than one with a practical elevation of 5 metres to allow car traffic to pass underneath. Plans for building an elevated metro system always seem to cause objections of residents. But when the line is taken into use the objections disappear and many have the opinion that it is indeed the best solution to decrease traffic congestion. With the realisation of metro stations, municipalities are able to develop certain areas. Furthermore reference projects show that it is possible to create elevated metro systems which have a very small environmental impact. Noise nuisance which is an important issue can namely be minimized by taking some measurements.

From a social point of view the stations are made very transparent, especially for security reasons. Transfer stations should have an island platform as this provides a smoother transfer of passengers. For intermediate stations the choice between an island platform and side platforms depends on the space available at ground level and the cost. The stations often consist of three levels: ground level with the access points; first level with the concourse; and the second level with the station platform(s). Currently most high elevated metro systems are made of concrete. The railway girders consist of prefabricated segmental box girders with external prestressing and span about 35 metres. Mostly the columns are cast in-situ and the girders are erected by a launching truss in order to limit the hindrance below. The span-to-height ratio of elevated metro lines ranges between 2 to 4. A relative high ratio is important for the aesthetics of the line as a low value would mean more visual hindrance. It is however important to take into account the material and construction prices which can differ from country to country.

3. Vertical transportation

References: [1] [19] [i9] [i11] [i17] [i20] [i26] [i30] [i32]

3.1 General

When a metro system is elevated till a certain height it is important to design the station in such a way that it is still easy accessible. Most stations are mainly served by stairs, although escalators are applied more and more. Escalators are often applied in stations where the vertical distance between the concourse and the platforms becomes too large. For long distances people will use the escalator as it takes less effort than walking the stairs. The use of escalators does not automatically mean that the transfer of people increases. When people are not walking on the escalator but stand still, it is about as fast as taking the stairs. Especially when it is crowded it can be seen that people are standing still on escalators which does not contribute to a larger transfer capacity. For disabled persons elevators can be found in most stations. These elevators are mostly used by disabled persons as it is much faster to take the stairs when one is healthy. To make the station accessible for disabled persons, it could also be an option to apply moving walkways. This way, elevators are not necessary anymore. The inclination of moving walkways ranges between 3° to 12° which means that to cover a large height a long walkway is needed. This longer walkway will decrease the transfer capacity compared with escalators and stairs as most people using the metro system are not disabled. The application of moving walkways would thus be an inefficient and expensive solution. For this reason stairs and escalators are often chosen as means of moving large groups of people vertically in stations and moving walkways can be found in malls where many people with shopping trolleys are walking.

The vertical transportation in high-rise buildings shows that elevators are the major means of transportation and stairs are used often for small distance travel and are also applied in case of emergencies. Escalators are mostly left out of high-rise buildings. For low-rise buildings with a high density of people it shows that commonly an escalator travel is faster than an elevator travel for the first two floors travelled. The elevators in the high-rise as well as low rise buildings are multistop elevators and the elevators in stations are generally two-stop elevators. This should mean that an elevator travel time would even more decrease in stations. However, in stations it is not only important to consider the travel time but also to move large groups of people within a limited time. Elevators have a limited capacity and the average waiting time is therefore an important issue to notice. To transfer many people with elevators, a lot of elevators are necessary. Besides the elevators there is always a need of stairs in case of emergency. The possibilities of emergencies are important factors for the design of station layouts. For this reason the major means of vertical transportation in stations are stairs and escalators. Underground stations of 30 metres deep are provided with escalators and stairs without extensive use of elevators. An elevated metro station high above street level has to satisfy the same demands as an underground metro station. The question however rises till what height an elevated metro system can be made accessible by stairs and escalators without the installation of an elevator system as major means of transportation.

3.2 Stairs

Stairs are used for centuries as means of moving pedestrians from one level to another. The average inclination of stairs in public buildings is 30°. Stairs are designed to handle the full flow of pedestrians in case of emergency. In order to prevent that people stumble and fall of the stairs all the way down it is obligated to install terraces for every 4 metres of stair height. The chance of falling of the stairs is higher for running downwards. These terraces are therefore especially important in case of evacuating an elevated station as one needs to go downwards.

3.3 Escalators

Escalators offer pedestrians the possibility to move in vertical direction with less effort than when walking the stairs. They are mostly applied for the upward direction as walking down the stairs is not very strenuous. But also escalators running downwards are not rare. Because people mostly stand still on crowded escalators, walking the stairs could even be faster. However, when the covered distance rises, the consideration to take the stairs disappears for most people. The handling capacity of escalators is affected by four factors:

- Speed. Commonly speed for a metro station is 0.65 m/s.
- Step widths. Widths of 600 mm, 800 mm and 1000 mm are available, the latter allowing two columns of passengers to be carried.
- Inclination. This is usually 30°.
- Boarding and alighting areas. These areas encourage pedestrian confidence and assist the efficient and safe boarding of escalators. The average pedestrian boarding/alighting stride is 750 mm.

To give an impression: the practical handling capacity of an escalator with a speed of 0,65 m/s and a step width of 1000 mm is 98 persons/minute.

The metro line Noord/Zuidlijn in Amsterdam which is currently under construction will have some underground stations which are only accessible by escalators and elevators. This means that the escalators have to handle the flow of people in case of emergencies. The use of escalators as mean for evacuation in the design of a station is quite unusual in the Netherlands. The application of escalators without terraces is approved after research turned out that it would satisfy in emergency circumstances. The use of escalators higher than 4 metres are allowed in case of:

- Evacuate in upward direction.
- The escalators run in upward direction or stand still.
- The dimensions of the escalator steps (rise height and tread depth) are the same as a stair according to the building code (Bouwbesluit).

The deepest metro station of the Noord/Zuidlijn is the Ceintuurbaan with a depth of 26.5 metres below street level. Station Angel of the London Underground has an escalator length of 60 metres, which is one of the longest in the world. As the underground station become deeper, escalator rises exceed 30 metres. For elevated stations the evacuation is in downward direction. This means that stairs or escalators with terraces are necessary. Escalators with terraces are expensive and are less efficient than stairs that run downwards. For elevated stations it is therefore by all means recommended to use stairs because escalators with terraces are unwanted. Next to stairs, straight downward escalators can still be applied to make it even easier for the people to move in the normal situation.

3.4 Elevators

Elevators in stations are mostly not used as major means of vertical transportation. Stairs and/or escalators will fulfil this purpose as elevators will transfer the disabled persons. The elevators in the metro stations of the existing metro network in Rotterdam (RET) have a minimal standard of: 2.1 metres width, 2.0 metres depth and 1.0 metre door passage. When the elevated metro system will be realised in Rotterdam, it will probably join the existing metro network. This means that the elevators should have the same dimensions, because when one can enter a station with a small car or large object and at the destination one cannot leave the station if the elevator is smaller. This should be prevented or should be solved otherwise. With an assumed density of 5 persons/m2 the RET elevators have a capacity of 20 persons per flight. When two metro trains arrive and drop their maximum of about 250 passengers each and they all have to use the elevator means that many fast elevators are necessary. In quiet periods these elevators are however less used. There should thus be an optimum for vertical transportation by elevators. The needed capacity of the elevators can be reduced by allowing entrance to one metro train at a time. Fact is that elevators cannot contribute to a continuous flow of people and have a considerable throttling effect on pedestrian movement. Only for transferring large heights, elevators are chosen as major means of vertical transportation. In some stations escalator rises go to about 30 metres. Thereafter it seems to be that the use of elevators is more efficient. Metro station Hampstead for example has the deepest platforms on the London Underground network with an elevator flight of 55.2 metres. The passengers of Hampstead station can choose between 4 elevators and using the stairs (see Figure 28). In order to improve the capacity of one elevator flight it could be an option to use double-deck elevators. Therefore platforms to enter the upper car are necessary at both stops in the station. This saves the need for more elevator shafts. Besides passenger elevators also service elevators are required to supply the shop inside the elevated station.

Figure 28: Signage in Hampstead station

3.5 Conclusions

The possible means for vertical transportation inside an elevated metro station are: stairs, escalators and elevators. The use of moving walkways is not efficient enough. The stations will always have stairs as this is required in emergency circumstances. Also at least one elevator is necessary to make the station accessible for disabled persons. The choice between stairs, escalators or elevators as major means of vertical transportation depends on the height of the elevated metro station. For very small elevations stairs are chosen. When the height becomes larger and terraces for the stairs are necessary (rise of more than 4 metres), escalators are the best option. Elevators as major means of transportation are chosen if the elevation exceeds 30 metres.

3.6 Solutions

If the elevation of the metro station becomes too high this can cause problems for the evacuation time. When taking the stairs downwards takes too long another option should be available. An idea for this problem is connecting the elevated station with surrounding buildings by means of skybridges (overhead pedestrian walkways). This will reduce the evacuation time considerably.

Emergency circumstances can also occur outside the metro stations on the elevated track. When the distance between two stations becomes too large it could lead to an unacceptable distance to cover for the passengers. It is therefore necessary to provide extra emergency staircases between these stations.

4. Bridges

References: [3] [4] [5] [8] [10] [20] [i4] [i6] [i16] [i22] [i41]

4.1 General

The structure of an elevated metro railway is similar to that of a bridge. A bridge is a structure that crosses over a river, valley or other obstruction. In this way it permits a safe and smooth passage of vehicles, trains and pedestrians. For an elevated metro railway obstructions are for instance roads, buildings and rivers. By elevation of the railway it will be grade separated from other modes of traffic. This enables the metros to drive fast and safe without hindrance. A bridge structure can be divided into an upper part (the superstructure), which consists of the deck, the floor system and the main trusses or girders, and a lower part (the substructure), which consists of piers, columns, footings, piles and abutments. The superstructure provides horizontal spans and carries traffic load directly. The substructure supports the horizontal spans elevating above the ground surface.

For the type of structure of an elevated railway there are many possibilities. The type of bridge is usually determined by factors such as loads, surrounding features, soil properties, bridge dimensions, aesthetics, transportation of construction materials, erection procedures, construction cost and construction time. The choice for a bridge type is thus dependant of many factors and besides, it is integrally related to the chosen material. The different bridge types all have their own advantages and disadvantages. These qualities together determine the appropriate span range for a certain bridge type. The appropriate span lengths for the most common type of bridges are shown in Table 1.

Bridge type	Span range (m)
Prestressed concrete girder	10-300
Steel I/box girder	15-300
Steel truss	40-550
Steel arch	50-550
Concrete arch	40-425
Cable-stayed	110-1100
Suspension	150-2000

Table 1: Span range for common bridge types

The span ranges given in Table 1 are very wide and overlap each other. This table does thus not give information about which bridge type should be chosen. In order to choose the desired bridge type the most common bridge types are briefly described in this chapter. This will also result in a more refined overview of the span range of the bridge types. Together with information about the construction methods and maintenance this should give a better understanding of bridge types and its possibilities.

4.2 Bridge types

4.2.1 Girder bridge

A girder bridge is a bridge built of girders placed on bridge abutments and piers. It is a very common bridge structure in which the girders carry the loads directly towards the supports. Girder bridges are mostly made of steel and concrete which give satisfactory performances. The choice between the two materials depends mainly upon the cost of construction and maintenance. The most common types of girder bridges are briefly discussed below.

<u>Steel</u>

I-girder

An I-section is the simplest and most effective solid section of resisting bending and shear. A steel I-section may be a rolled section (beam) or a built-up section (plate girder). A plate girder can be considered as a deep beam and is built-up out of a steel plate. Rolled steel I-beams are applicable to shorter spans (less than 30 metres) and plate girders to longer span bridges (about 30 to 90 metres). Furthermore, I-sections can be classified as composite or non-composite. A steel section that acts with the concrete deck to resist flexure is called a composite section. Since composite sections use the properties of steel and concrete most effectively they are often the best choice. The depth-to-span ratio for a composite steel I-girder is usually about 1:25 and for a steel girder only about 1:30. I-rolled beams are usually used for simple-span lengths up to 30 metres for highway bridges and 25 metres for railway bridges.

Box girder
Box girders are used extensively in the construction of urban highway, horizontally curved and long-span bridges. Box girders have higher flexural capacity and torsional rigidity, and the closed shape reduces the exposed surface, making it less sensitive to corrosion. Box girders also provide smooth, aesthetically pleasing structures. There are two types of steel box girders: steel-concrete composite box girders and steel box girders with orthotropic decks (steel plates with longitudinal and transverse stiffeners). Composite box girders are generally used for spans of about 30 to 60 metres. Steel box girders with orthotropic decks are often used for longer span bridges (60 -100 metres).

Reinforced Concrete

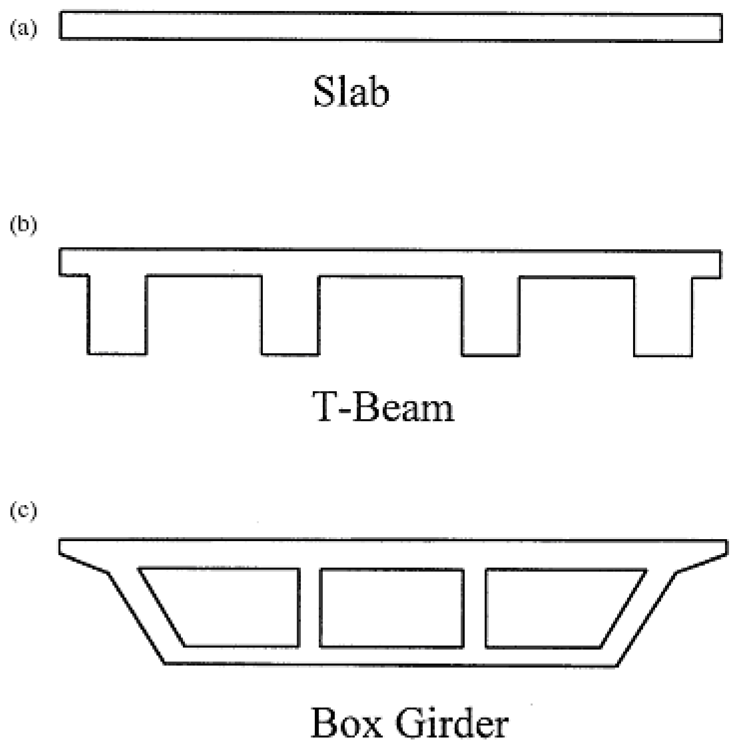

Figure 29: Typical reinforced concrete sections in bridge superstructures: (a) solid slab; (b) T-beam; and (c) box girder

Slab
A reinforced concrete slab is the most economical bridge superstructure for spans of up to approximately 12 metres. They generally require more reinforcing steel and structural concrete than girder-type bridges of the same span. However, the design details and formworks are easier and less expensive. The slab is neat and has a nice appearance (see Figure 29a). Common spans range from 5 to 13 metres, with structural-depth-to-span ratios of 0.06 for simple spans and 0.045 for continuous spans.

T-beam
T-beams are generally economic for spans of 12 to 18 metres (see Figure 29b). They however require more complicated formwork, particularly for inclined bridges. Structural-depth-to-span ratios are 0.07 for simple spans and 0.065 for continuous spans. The spacing of girders in a T-beam bridge depends on the overall width of the bridge, the slab thickness and the cost of the formwork. As rule of thumb the spacing of T-beam girders may be taken as 1.5 times the structural depth. The most commonly used spacing is between 1.8 and 3.1 metres.

Cast in-situ box girder

Box girders are often used to span 15 to 36 metres (see Figure 29c). Its formwork for inclined structures is simpler than that required for the T-beam. Due to the excessive dead load deflections, the use of reinforced concrete box girders for simple spans larger than 30.5 metres may become uneconomical. The depth-to-span ratios are 0.06 for simple spans and 0.055 for continuous spans with the girders spaced at 1.5 times the structural depth. The high torsional resistance of the box girder makes it particularly suitable for curved alignments.

Prestressed concrete

Slab
Cast-in-situ prestressed concrete slabs using high-strength materials are more expensive than reinforced concrete slabs. A prestressed slab can however carry larger loads and/or span larger distances than a reinforced slab. A precast prestressed slab is economical when many spans are involved (see Figure 30). Common spans range from 6 to 15 metres. Structural-depth-to-span ratios are 0.03 for both simple and continuous spans.

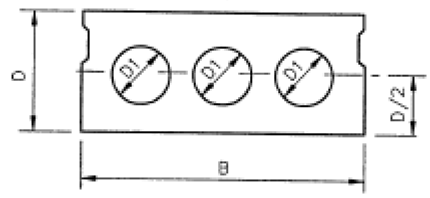

Figure 30: Precast prestressed voided slab section

Precast I-girder
Precast I-girders compete with steel girders and generally cost more than reinforced concrete girders with the same depth-to-span ratios (see Figure 31). The formwork for this girder is complicated, especially for inclined structures. Precast I-girders are economical for spans of 9 to 36 metres. These girders are available up to a length of about 50 metres. Structural-depth-to-span ratios are 0.055 for simple spans and 0.05 for continuous spans.

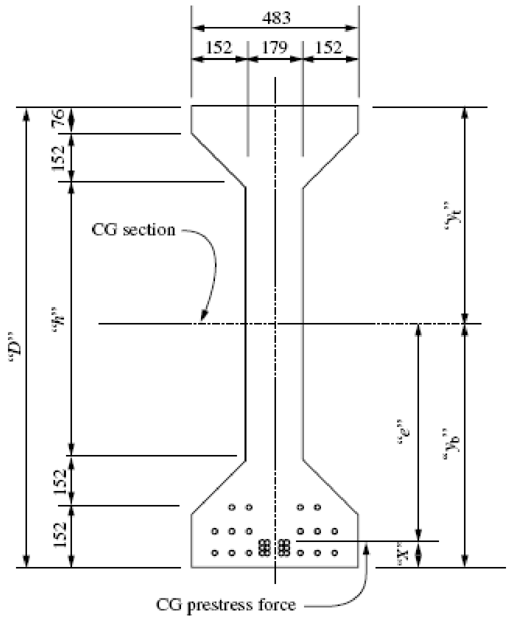

Figure 31: Precast I-girder section

Box girder
The shape of a cast in-situ prestressed concrete box girder is similar to the conventional reinforced concrete box girder. The spacing of the girders can be taken as twice the structural depth. Prestressed box girders can reach spans of 300 metres but are mostly used for spans of 30 to 183 metres. Once the span becomes too large the box girder becomes a cast in-situ segmental girder. Structural-depth-

to-span ratios are 0.045 for simple spans and 0.04 for continuous spans. Precast prestressed box girders are available for spans up to approximately 50 metres (see Figure 32). For larger spans multiple precast box girder elements are connected to each other by mean of post-tensioning. The selection between cast-in-situ and precast segmental is dependent of project features, site conditions, environmental and public constraints, construction time and available equipment. Table 2 lists the range of applications of some prestressed box girder bridges by span length. The high torsional resistance of the box girder makes it particularly suitable for curved alignments.

Span (m)	Bridge type
30-91	Cast-in-situ post tensioned box girder
30-91	Precast-balanced cantilever segmental, constant depth
61-183	Precast-balanced cantilever segmental, variable depth
61-305	Cast-in-situ cantilever segmental

Table 2: Range of application of some prestressed box girder bridges by span length

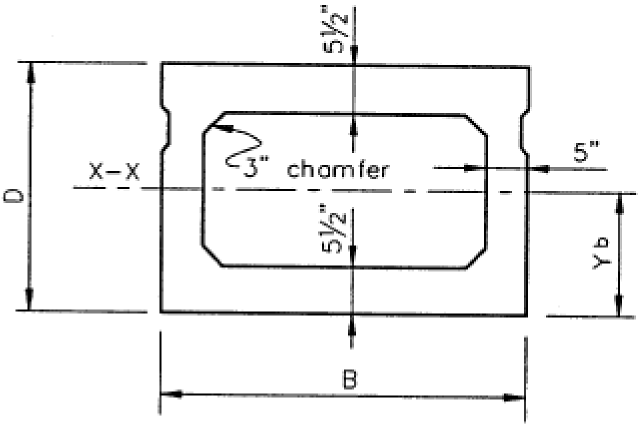

Figure 32: Precast box girder section

4.2.2 Truss bridge

The structural layout of a truss is shown in Figure 33 for a bridge with the deck located at the level of the lower chords. The floor slab, which carries the live load, is supported by the floor system of stringers and cross-beams. The load is transmitted to the main trusses at nodal connections, one on each side of the bridge, through the floor system and finally to the bearings. Lateral braces are attached to the upper and lower chords to resist horizontal forces as well as torsional moments. The portal frame at the entrance provides transition of horizontal forces from the upper chords to the substructure. Truss bridges are often made from steel, but wooden trusses can also be found. There are many types of truss bridges and they not all have the same structure as described above. The function of truss bridges however focuses on transferring loads via the main trusses towards the bearings. Trusses are an assembly of bars, not plates, and are thus relative easy to erect on site and are often the choice for long bridges. Truss bridges can make efficient use of the materials. Truss bridges have been an effective and efficient option for long-span bridges for years. As plate girder bridges have been utilized for spans of about 90 metres, box girders for spans of up to 300 metres and cable-stayed bridges for spans of about 150 to 600 metres, the use of trusses has declined over the last 25 years. Nonetheless, they remain a cost-effective bridge form, with many experienced fabricators and erectors. Steel trusses are applicable for spans of 40 to 550 metres.

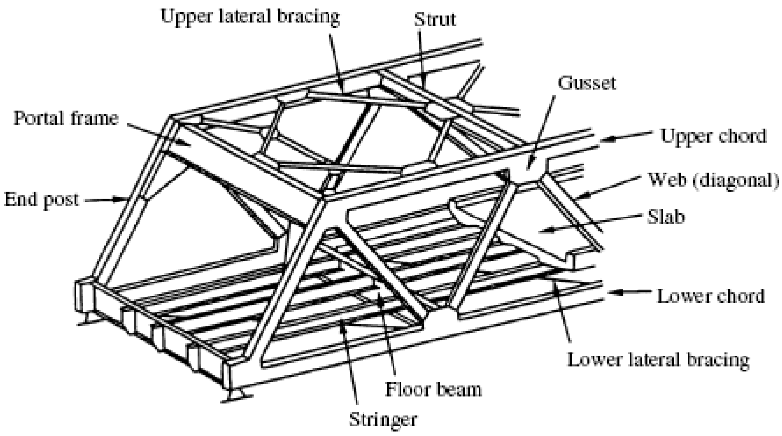

Figure 33: Structural layout of a truss bridge

4.2.3 Arch bridge

An arch bridge includes the deck and the supporting arch. The perfect arch, theoretically, is one in which only a compressive force acts at the centre of each element of the arch. It is practically however impossible to have a perfect arch bridge except for one loading condition. The arch bridge is usually subjected to multiple loadings which will produce bending moment stresses in the arch. These bending moment stresses are generally small compared with the axial compressive stress. That is why the arch is often made of materials that have a high compressive strength such as concrete, stone and brick (see Figure 34). Due to the curved form of the bridge, vertical as well as horizontal forces act at the abutments. These horizontal forces have to be taken by the soil or by a tension tie. The latter is known as a tied arch bridge and is mostly made of steel. Other variations on the standard arch bridge are the suspended deck arch bridge (the arch supports the deck by means of suspension cables, see Figure 35) and the supported deck arch bridge (the arch supports the deck by means of a number of vertical columns, see Figure 36). The arch bridge is very competitive with truss bridges in spans up to about 275 metres. If the cost is the same or slightly higher for an arch bridge, then from aesthetic considerations the arch bridge is often selected instead of the truss bridge. For longer spans, usually over water, the cable-stayed bridge has been able to be more economical than tied arch spans. The perfect arch will continue to be built for long spans over inaccessible deep valleys where appropriate. The rise-to-span ratio for arches may vary widely because an arch can be very shallow or could even be a half-circle. Most arches would have rise-to-span ratios within the range of 1:4.5 to 1:6. An arch bridge can be applied for spans of 40 up to 550 metres.

Figure 34: The Alcántara Bridge

Figure 35: The Sydney Harbour Bridge

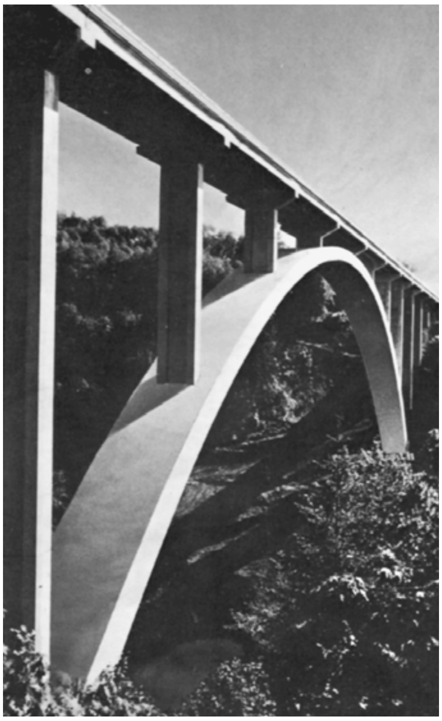

Figure 36: The Cowlitz River Bridge

4.2.4 Cable-stayed bridge

The structure of a cable-stayed bridge is shown in Figure 37. The bridge mainly carries vertical loads acting on the girder. The stay cables provide intermediate support for the girder so that it can span a long distance. The basic form of a cable-stayed bridge is a series of overlapping triangles which consists of the pylon, the cables and the girder (see Figure 38). All these members are mainly under axial forces: the cables under tension and the pylon and the girder under compression. By loading the members axially they act very efficient. The pylons form the primary load-bearing structure and if the bridge is symmetrical, all static horizontal forces are balanced ensuring it only needs to resist horizontal forces from the live loads. Cable-stayed bridges are economical for spans up to about 1000 metres. They are economical because of the lightness of the deck which is supported by the cables.
The disadvantage of such a light and flexible deck is that it is not very capable of spreading the live load over a larger span compared with a stiffer bridge deck. Cable-stayed bridges have a span range of 110 to 1100 metres.

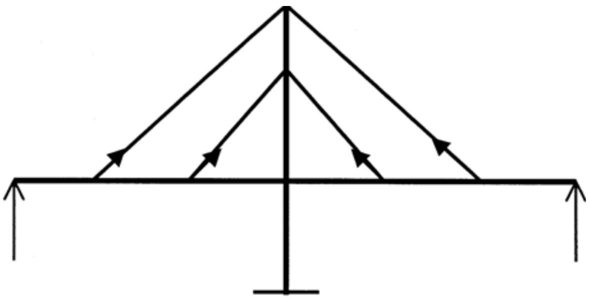

Figure 37: Structure of a cable-stayed bridge

Figure 38: The Millau Viaduct

4.2.5 Suspension bridge

A suspension bridge is a type of bridge in which the deck is hung below suspension cables on hangers (see Figure 39). The basic structural components of a suspension bridge are:

1. Stiffening girders/trusses: Longitudinal structure which directly carries the vehicle load and secures the aerodynamic stability of the structure.
2. Main cables: A group of parallel cables which support the stiffening girders/trusses by hangers and transfer loads to the towers.
3. Main towers: Intermediate vertical structures which support main cables and transfer bridge loads to the foundations.
4. Anchorages: Massive concrete blocks which anchor the main cables and act as end support of a bridge.

The main forces in a suspension bridge are tension in the cables and compression in the towers. Due to the intermediate support by hangers, the girders/trusses can be made quite slender. Important is however to notice the stability in longitudinal and transversal direction as this is often normative for the girders/trusses. The relative low deck stiffness compared to other types of bridges makes it more difficult to carry heavy rail traffic where high concentrated live loads occur. Another disadvantage is the large horizontal forces on the soil near the anchorage blocks. Building an anchorage block in soft soil would therefore require a large and expensive foundation. With this type of bridge longer main spans are achievable and less material may be required than with any other type of bridge. This reduces the construction cost and makes it most suitable for very-long span bridges. The span range of a suspension bridge is 150 to 2000 metres.

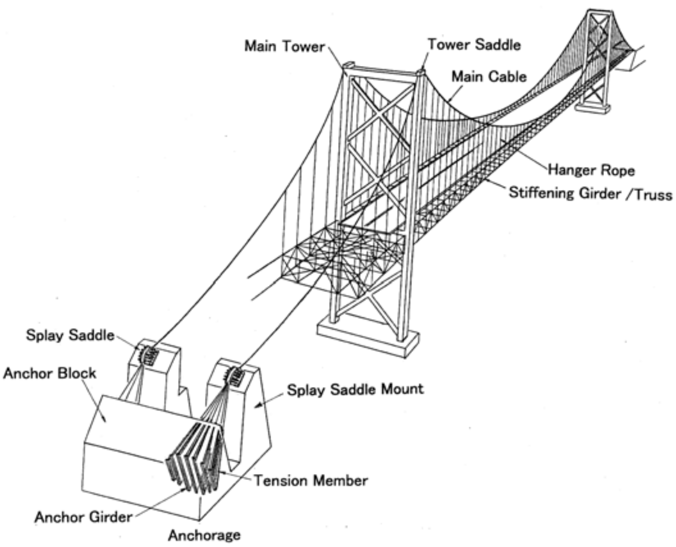

Figure 39: Suspension bridge components

4.2.6 Analysis bridge types

The bridge types above are the most common bridge types. They all have their own advantages and disadvantages as briefly described. In Appendix 4: Span range for bridge types, the appropriate span ranges for the above described bridge types are given. This gives a clear overview and easily shows the possible bridge types for a specific span. There is a division between the small-span and long-span bridge types as the span range between the bridge types is too large in order to give a clear overview.

The longest possible span is however not the most important for an elevated metro system. More important is that it fits in the proportions of the city and can follow its alignment within the city. To follow its alignment a metro line requires horizontally curved tracks. An elevated metro structure should therefore be a bridge type which is able to follow a horizontal curvature. A curved track can be made by building several shorter, straight spans with the curved rails on top of it. This however does not give a fluent line and is from an aesthetical point of view often not desired. Box girders and curved steel girders are often chosen for a curved bridge. Curved steel girders do not have high torsional resistance, but this can be solved by connecting the girders with the deck and/or cross-beams perpendicular to the girders. Box girders on the other hand have a high torsional resistance which makes them very suitable for horizontal curved bridges.

A fluently horizontally curved elevated railway is not possible with a suspension bridge as the cables between the towers can not be horizontally curved. For a cable-stayed bridge there will arise large transversal forces upon the pylon and eccentrically forces upon the bridge elements. This is the same for a horizontally curved arch bridge and for a steel truss bridge. For these four bridge types it would be far more economical to build several shorter straight spans. A horizontally curved structure is more difficult to build than straight structures and as the spans become larger the forces upon the columns may become too large. Too large spans for a horizontally curved railway are thus from economical point of view unwanted. It is better to have several small straight spans than a few large straight spans as the latter results in a very noticeable stepwise curved railway.

Reference projects show that the mean span with a box girder is 35 metres. The graphs in Appendix 4: Span range for bridge types, show however that this is short compared to the achievable spans with box girders. The maximum span for the different bridge types is deducted from straight highway bridges. Because the load for a metro bridge is less it can be noticed that the curvature of the elevated structure/torsional resistance is important to determine the span length. It can be concluded that the choice of the bridge type is not only determined by span range but is among other things also determined by the application within the city. The final decision for a certain bridge type can be made by taking everything into consideration and not only the largest span as this for instance creates a smaller physical barrier.

4.3 Construction methods

There are different methods to construct a bridge. Determining the method of construction and bridge type requires taking into account the required span length and the existing site constraints. Furthermore the construction schedule, the contractor's equipment or the size of the project may also be determining factors to prefer one method over another. The advantages and disadvantages of various approaches must be analyzed early in the conceptual design phase to determine the best one. This section discusses the suitability of each method, when its use is feasible, the construction sequence of each method, their advantages and limiting span ranges. The methods of construction discussed are (the first seven methods concern construction methods for concrete bridges):

- Cast-in-situ construction
- Balanced cantilever
- Precast construction
- Span-by-span construction
- Incremental launching
- Cable-stayed construction
- Arch construction
- Steel bridge construction

4.3.1 Cast-in-situ construction

Cast-in-situ construction is a method where the concrete is poured into the formwork at the construction site. The concrete is delivered by trucks or is produced at the site. This way there is no need of complicated transport of large bridge elements and by continuous pouring a large monolith structure can be constructed. This method is commonly used for short span bridges for the cost-effective construction of solid, voided or ribbed reinforced concrete slab bridges. It is a flexible method of construction which can realise unusual geometrical shapes. A span is cast in one continuous pour and is commonly supported by a standard falsework with plywood formwork. Where cast-in-situ construction is used for longer span bridges, the required falsework becomes more sophisticated. Semi or fully mechanical falsework will require a specialized contractor. Semi mechanical falsework generally consists of steel beams or trusses which are placed between temporary supports. Fully mechanical falsework is a self launching gantry with steel lined shutters. It will take about 2 to 6 weeks to construct a span with a semi mechanical system and 1 to 2 weeks with a fully mechanical system.

4.3.2 Balanced cantilever

The construction of a balanced cantilever method begins at the bridge piers. From there cast-in-situ segments of 3 to 5 metres length are poured into the special formwork. The formwork moves in tandem with each segment. This way the structure stays in balance (notice the name of this method). The completed segments are used as erection platform and launching base for the subsequent segments. The construction continues until it reaches the midpoint of the span where it will be closed with the cantilever from another pier. The end cantilever is temporary supported to have stability before the end cantilever is completed (see Figure 40). It is a flexible and efficient method which gives little disturbance to its surroundings. However, it is a relative slow building method. By utilizing precast segments this restriction can be improved. This construction method is chosen where a bridge has few spans which range from 50 to 250 metres.

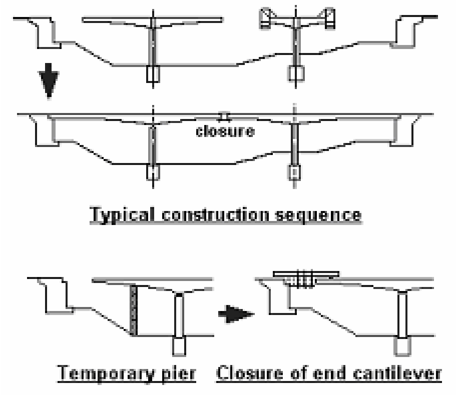

Figure 40: Balanced cantilever method

4.3.3 Precast construction

Precast segmental decks
Precast segmental deck construction is used for long bridges where the deck depth is difficult for cast-in-situ construction. For this system generally box girder segments are used. These segments can be 2 metres deep, 2.5 to 4 metres long and carrying a deck up to 15 metres wide. The segments are connected either by internal or external prestressing. The construction has a repetitive character which can be very efficient in case of a tight organized time schedule. The balanced or free cantilever method about a pier is a preferred choice. With this method a crane or self launching gantry system can place up to six segments per day. The number of constructed spans per week for internally prestressed segments is considered to be one and for externally prestressed segments it is three.

Precast deck
Precast deck construction is often used for the construction of long viaducts. With this method a complete precast deck can be placed upon the columns at once. The decks are placed by a large crane or a gantry. The capacity of a mobile crane is currently up to 1200 tons. By using two cranes the capacity can even be doubled. It is a very fast erection method with a rate of construction of 2 spans per day using a gantry. It is however very important to have an organized time schedule and is very dependent of the timely delivery of the prefabricated decks. Transportation of the precast deck to the construction site should also be considered because exceptional transport is needed. This can be done by truck, ship or by rail and is often done at night, in order to limit the disturbance of the normal traffic. This transportation is expensive but is not necessarily a negative aspect as there is no transportation of materials, scaffolding, formwork etc. needed.

Precast beams
Precast beam decks are generally used for short span bridges ranging from 5 to 50 metres. The beams are placed by a crane which has a rate of construction of approximately four beams a day. A cast-in-situ slab top deck is normally used with an expected rate of construction of one span a week. As mentioned before it is important to examine the transportation towards the construction site.

4.3.4 Span-by-span construction

Span-by-span is a relatively new construction technique. It is considered to be the most economic and rapid method of construction available for long bridges and viaducts with individual spans up to 60 metres. This system makes use of precast segments which are continuously placed from one abutment to the other. The segments can be positioned by a temporary staying mast system or by a launching truss system. The latter is more common. The launching truss with sliding pads is braced over two piers. The segments are transported by truck or ship to the span under construction. Each segment is then placed on sliding pads and slid into its correct position. Once all the segments are in position the segments are connected by longitudinal prestressing. Finally deck joints are cast and closed and prestressing ducts are grouted. When the span is completed the launching truss moves to the next span where the construction cycle starts again until the bridge is completed.

4.3.5 Incremental launching

For bridge decks greater than 250 metres in length, the incremental launching method can be considered. With this method of construction the bridge deck is built in sections by pushing the structure outwards from an abutment towards the pier. The sections are cast contiguously, one after another, and are then stressed together. The superstructure is launched over temporary sliding bearings on the piers until the bridge is completed. In order to keep the bending moment low in the superstructure during the extrusion phases, a launching nose made of steel is attached to the front of the bridge deck. In-situ deck segments range in length from 5 to 30 metres. The spans should not exceed approximately 60 metres and the bridge sections must be constant. Furthermore the superstructure of the bridge has to be continuous over the whole length and straight or have a constant curvature.

4.3.6 Cable-stayed construction

Cable-stayed construction is the most common construction method for bridges which span more than 300 metres. Cable-stayed bridges can be made from concrete or steel though a combination is often chosen. With this method the deck segments are supported by stay cables which transfer the loads towards the pylon. The construction of the deck starts near the pylon and is built segment by segment outwards. Concrete deck segments can be either precast or cast-in-situ by travelling shutter arrangement. The structural layout of cable-stayed bridges results in large horizontal forces in the deck. The pylons are large as it also includes anchorage of the stay cables and carries the whole bridge. This construction method does not require scaffolding underneath the bridge which saves a lot of work and the hindrance stays limited.

4.3.7 Arch construction

Nowadays arch bridges are mostly built of reinforced or precast concrete. Arch construction often uses expensive formwork and scaffolding. The development of modern construction methods has made it possible to construct without the need of this traditional supporting system. However, the abutments still must be well founded on rock or solid ground. Arch bridges are often the most economical choice for bridges which cross over inaccessible landscape. Two construction methods which are most commonly used are:

- Cast-in-situ free cantilever method
  This involves the partially built arch being tied back to rock anchors in the valley slopes.
- Slip formed sections
  This involves half arch section being held vertically over each abutment and then rotating each arch section into position.

4.3.8 Steel bridge construction

Steel bridge components are fabricated into members in the workplace and are then transported to the construction site for assembly. Ideally all constructional work should be completed in the workplace to get the highest quality in the minimum construction time. Maximum length and size are preferred for the members of the bridge. However, the size of the elements is limited by transportation and erection restrictions. Common construction methods for steel bridges are crane erection, launching truss erection, cable erection and cantilever erection (see Figure 41). The best way to connect the members is by bolting as welding on site is more complicated and expensive.

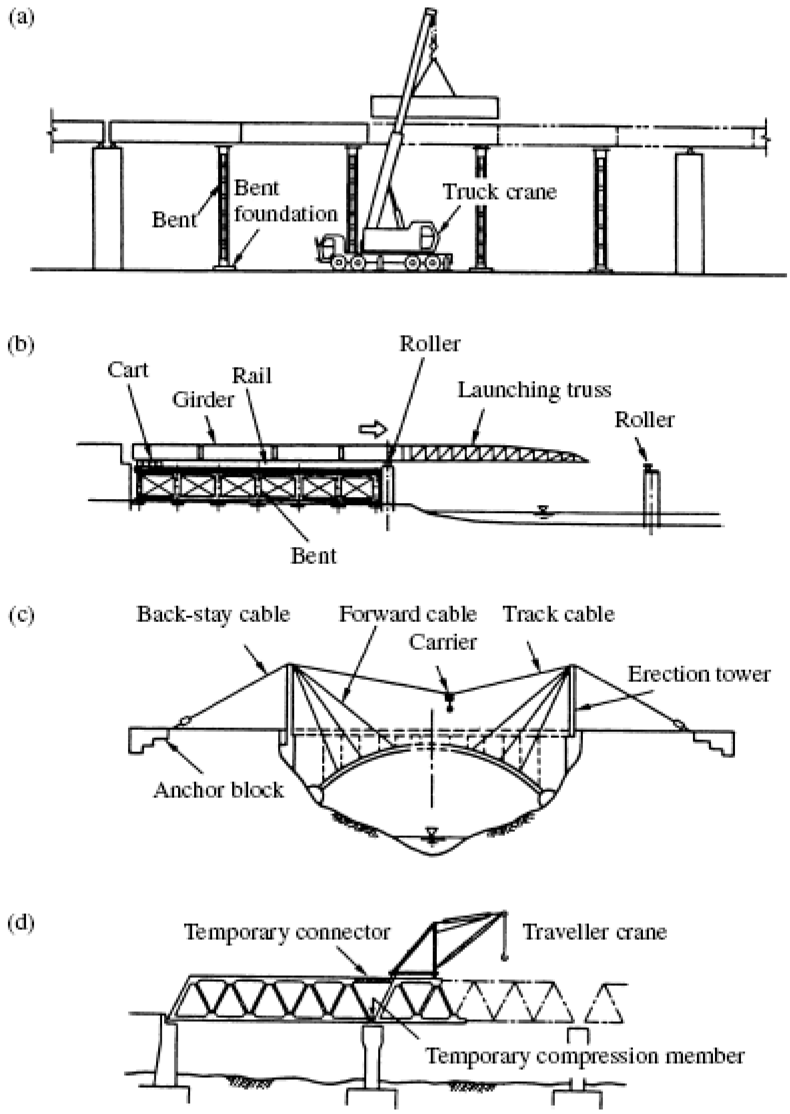

Figure 41: Erection methods: (a) crane erection, (b) launching truss erection, (c) cable erection and (d) cantilever erection

4.4 Maintenance

The life span of a bridge is about 100 years. During operation, the bridge will need maintenance and occasionally replacement. Four areas of the bridge whose functional lifespan is less than that of the bridge structure and thus will require replacement at some stage are: surfacing, waterproofing, movement joints and bearings. In general, bearings and movement joints have to be replaced at least once during the operational life of the bridge. It is therefore important to design the bridge such that it can be properly inspected and maintained. Inspection can be done by using permanent or temporary access provisions. Permanent access provisions should be incorporated in the bridge structure and are expensive. More common is inspection using a hydraulic platform. This is applicable up to a limited height. If this is not possible, inspection can be done using abseil ropes. This is however very time consuming but can still be far more economical than a permanent access provision. From an economical point of view an elevated metro railway on land probably will be inspected with hydraulic platforms. When the elevation becomes too large an alternative solution should be applied. A metro railway has emergency walkways which enable the inspection on top of the viaduct. For the replacement of a part of the bridge it is better to have a structure which can easily be dismantled. This opts for a simple statically determinate supported structure. Continuous and integral structures are however more durable (e.g. no water can leak to the bearing pads, piers and abutments leading to corrosion). It is recommended not to use half joints as they are difficult to inspect and maintain and external post-tensioning should be designed to allow inspection and testing without traffic restrictions (see Figure 42). By taking into account the maintenance and replacement of the bridge in the design phase it is possible to prevent many problems which saves a lot of money.

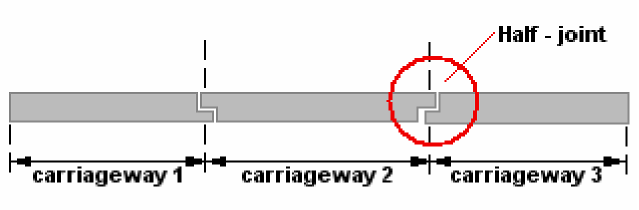

Figure 42: Half joint

5. Application of an elevated metro system in Rotterdam

References: [10] [i38]

5.1 General

Some parts of the Rotterdam metro system are already elevated. The Nesselandelijn viaduct for example has an elevation of 6 metres above street level. This elevation allows traffic to pass underneath the metro railway. At the same time the metro runs without any hindrance, which is quicker and safer than running without a right of way. As mentioned before a right of way for metros is also possible by placing it underground or at-grade. The former is however very expensive and takes a lot of time and the latter forms a physical barrier. An elevated metro system is cheaper and faster to construct than an underground system and does not forms a physical barrier which does an at-grade system. That is why there is an increase in construction of elevated railways. The Nesselandelijn has a practical elevation but many people find that it forms a visual barrier. Also other examples showed that an elevation of about 5 to 6 metres is not recommended in many cases. However, there is a trend towards using significantly taller columns in the range of 10 to 12 metres to reduce the visual impact of the railway by placing it farther overhead. This approach also has a pleasant side effect: it improves the view for metro passengers. The question rises how large the elevation and span of the railway must become for an application of an elevated metro system in Rotterdam.

An important requirement for an elevated metro system is that it must be aesthetical. The aesthetics of an elevated metro system often seems to cause fuss. Determining an ideal span-to-depth ratio is an essential factor in the overall aesthetic appearance of the structure. It influences the visual impact of the structure within the surrounding landscape. Many options exist that optimize the structural efficiency of the superstructure while creating an elegant structure. Creating the most aesthetically pleasing combination of span length and superstructure depth is often an iterative process. Based on experience, span-to-depth ratios ranging from 20 to 30 will result in superior aesthetics. A span-to-depth ratio of 15 on uniform spans is also considered visually appealing, but less than 15 is not preferable. In order to create an aesthetic elevated metro system it is further important to construct small low-visual impact railways with slender columns. By application of spans with a variable depth and sculptural curved columns the structure can be made even more attractive. However, maintaining a constant depth as well as a constant cross-section will greatly simplify casting and erection operations and thus reduce construction costs. For longer span bridges it is often more economical to vary the depth of the superstructure instead of maintaining a constant depth. A deeper box girder section is required to resist the higher forces closer to the piers, while at mid-span a shallower section is adequate to resist the lower forces. The structural depth, therefore, is often gradually decreased over the length of the span to minimize quantities and to reduce the weight of the structure. This can be achieved with graceful, sweeping curves that will enhance the visual appeal of the structure by making it appear more slender and elegant.

Beside the span-to-depth ratio of the railway also the height and the span of the railway are important factors. A high span-to-depth ratio with small spans results in a structure with many columns. This is not aesthetical and enhances the feeling of a visual barrier. By elevating the railway to a larger height than the span length the spatial perception reduces as it looks like that the railway is supported by too many columns. For an aesthetic structure it is therefore necessary to have a span-to-height ratio of at least 1. A higher ratio will even be better. However the ratio can not be chosen too large as this reduces the height and as mentioned before the railway should have a certain elevation to reduce the visual barrier. A higher elevation also has the advantage of less noise pollution at street level as the distance is larger. Also the shade intensity is lower for a higher elevated structure because of more diffused sunshine. Furthermore it can overpass buildings and trees if necessary. With a large span and a large height the land requirement is small. This is preferred as it provides the opportunity to use the land underneath for other purposes which results in multiple land use.

Nobody wants infrastructural structures in his backyard, well known as the NIMBY-behaviour (Not-In-My-Back-Yard). It is however important that the city is made accessible by infrastructure. Motorways often push down nearby residential land values. But proximity to a metro station often triggers commercial and residential growth, with large office and housing blocks being constructed. Bundling an elevated metro line with railroads and roads has big advantages. Combining of physical and visual barriers causes less hindrance. Moreover, bundling makes the implementation of the project easier. An elevated metro structure does not automatically mean destruction of landscape. Infrastructural structures can, if well designed, give the area a certain appearance and work as a landmark.

5.2 Elevated railway

Rotterdam is a city with relative many low-rise buildings. The implementation of a metro system elevated to a large height would thus influence the skyline to a large extent. A new metro system in Rotterdam would, if chosen to, be built within the existing city. Therefore it should fit into its urban framework. As mentioned before, bundling of infrastructure has big advantages. Hence an elevated metro system should for the greater part be bundled with roads and railways. As it follows the street pattern of the city the structure should be quite flexible. This means that the spans cannot be too large. Curves can be made by smaller straight spans or by horizontally curved spans. The latter gives a more fluent alignment and provides the same span lengths along the track. Due to its form it is however more difficult and expensive to build. The goal in establishing the span length is to determine the optimal span length and consistently utilize this length throughout the project as much as possible. This will increase the efficiency of the project by introducing repetition into the construction operations, resulting in smaller construction costs. The balanced and repetitive span lengths also provide continuity in appearance, resulting in visually appealing structures. The extreme large bridge spans with cable-stayed and suspension bridge types are thus not applicable. These bridge types would result in a very rugged alignment and should be elevated above almost everything. Besides it is unwanted to have a superstructure with cables. The structure should have a slender appearance, it should fit into the city and should be economical.

Rotterdam has many dwellings which have a height of about 9 metres. A very large elevation of 50 metres would be inappropriate here. An elevation of 5 metres turned out to be not successful from a social point of view. The minimum height of the structure should be 9 metres as people within an average building of 9 metres high can look straight out of the window without seeing the railway (reducing the visual impact). This also results in the fact that metro passengers are able to oversee the city. The maximum span of the railway for application in Rotterdam is chosen to be 45 metres. The reason for this span length is twofold. Firstly with this span length it is expected that the metro alignment can follow the cities street pattern and fits into the proportions of the city. Secondly this is seen as the most economical span as it can be built with in-situ concrete, precast concrete and steel girders. By choosing this span length one is independent from one construction material and its price. Moreover, one is able to involve more contractors with the realization to enlarge the competition and thereby saving costs. To create an aesthetic structure the span-to-height ratio should be at least 1. For the application in Rotterdam it is chosen to have a span-to-height ratio of 3 to create an aesthetical appearance. This means that for a span of 45 metres the elevated height becomes 15 metres.

The elevation of the metro system thus ranges from 9 to 15 metres. An impression of the minimum and maximum elevated metro structure within different residential street widths is shown in Figure 43. Especially for the minimum elevation of 9 metres the small streets become very dark as there is lack of sunshine. The maximum elevation creates a much more open and clear street view. Reference projects showed a range in elevation of 5 to 12 metres and a range in the mean span of 20 to 35 metres. As an elevation of 12 metres becomes more common a new metro system in Rotterdam should have an elevation of 15 metres. This is decided because of the aforementioned advantages with regard to an elevation of 9 metres, the challenge for further elaborating the design for this thesis and because Rotterdam is not just a city but wants to distinguish itself from other cities. Besides, if the elaboration of the elevated railway with a span of 45 metres turns out to be an appropriate structural design it is still possible to diminish the height.

The elevated metro system which will be further elaborated will thus have a height of 15 metres and a span of 45 metres.

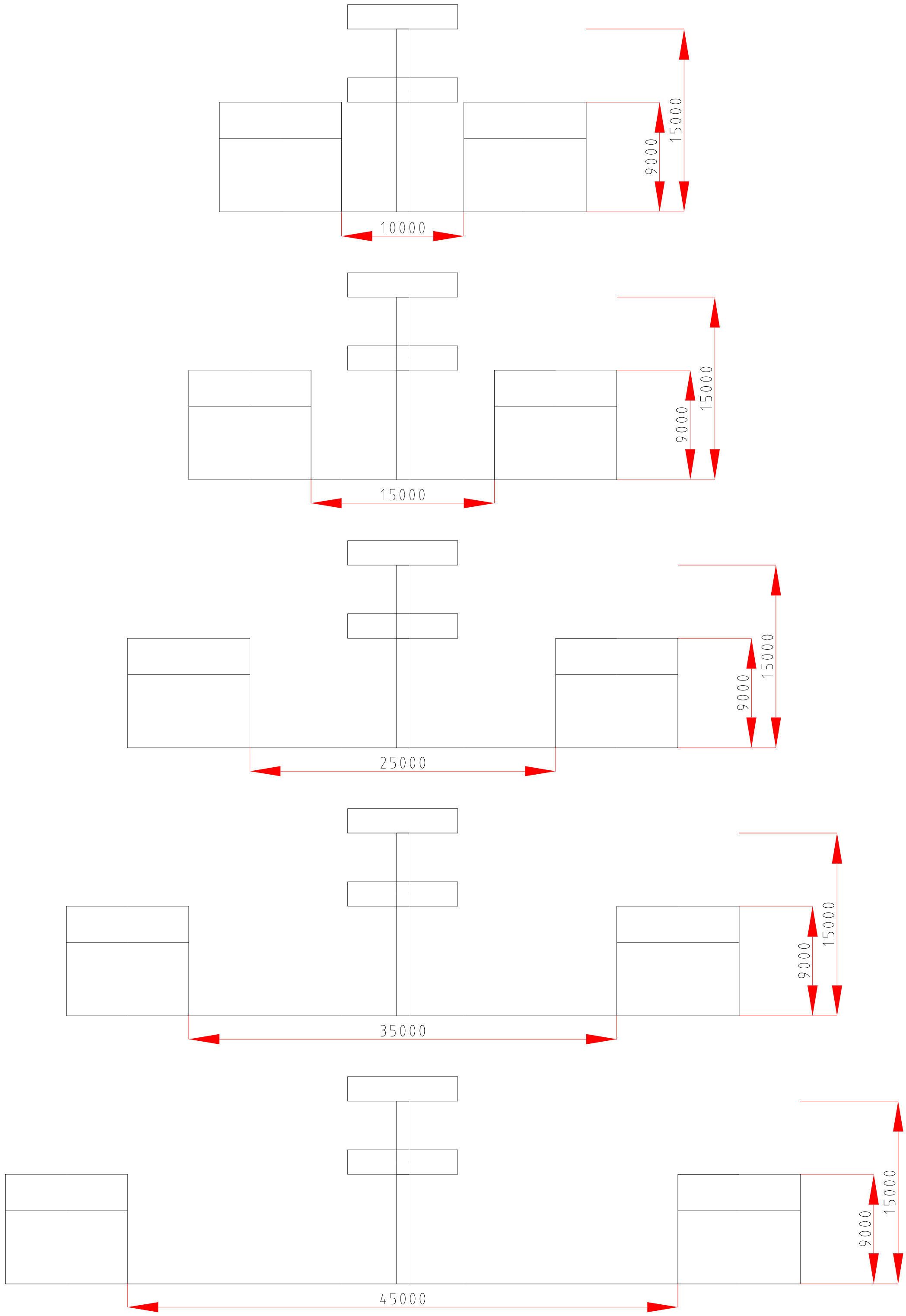

Figure 43: Impression of the minimum and maximum elevated metro structure within different street widths (in mm)

5.3 Stations

With an elevation of 15 metres of the railway, the stations platform is situated 16 to 17 metres above street level. Because the elevation is less than 30 metres, escalators should be chosen as major means of vertical transportation within the station. In case of emergency an elevated station should be provided with stairs which can handle the maximum expected capacity. An elevator will transfer the disabled persons. Along the metro line the stations can be built as side platform stations or as island platform stations. Side platform stations have the advantage that the railway can continue without splitting. An island platform station has the advantage that the number of stairs, escalators and elevators is only needed for one platform. Besides it creates a better social secure environment and is more suitable for cross-platform interchange between different lines. The choice between the two station types would probably be a financial dilemma. The stations should have a very spacious and open appearance as this is required to enhance the social security. Furthermore the stations should be accommodated with security cameras and RET employees to create a safer environment and for providing other services.

5.4 Possible applications

Vertical city

When stations are situated close to other medium- or high-rise buildings it could be an option to connect them by means of skybridges (overhead pedestrian walkways). This can create, if applied between more buildings in that area, a second level of pedestrian traffic. With this multiple land use and two levels it can set the trend towards the vertical city with multiple levels of horizontal traffic. It could also be an option to integrate the concourse inside the buildings and connecting the platforms with skybridges. An even more sophisticated option would be to build the whole station within a building with the railway passing through. These solutions are however very outrageous for the time of speaking and are not taken into further consideration.

Aesthetics

Aesthetics is an important issue for this metro system because the elevation of 15 metres will also make it a landmark. The structure should therefore have an attractive appearance. This can be achieved in many ways. One way is to cover the columns with ivy (see Figure 44). Plants often create a pleasurable effect and they bring more green into the city streets. The C02 emission in the city would thereby also become less.

Integrated walkway/cycle way

An option could be to integrate a pedestrian walkway or cycle way with the elevated metro system (see Figure 21). This allows a fast and safe movement for pedestrians and cyclists without hindrance from other means of transport. With the walkway/cycle way beneath the railway it can also offer protection against the rain (depending of the wind). An elevated cycle way could be the solution for Rotterdam to create a city which is more attractive for cyclist. Major disadvantage is that it will enlarge the visual barrier.

Figure 44: Column covered with ivy

6. Ultra High Performance Concrete

References: [2] [6] [7]

6.1 Material

Ultra High Performance Concrete is a result of the search for a concrete with a higher strength. Conventional concrete is currently still the most used concrete, but High Performance Concrete as well as Ultra High Performance Concrete have a high potential of application and are utilized more and more. Considering the compressive strength the following division can be made between the three types of concrete:

• Conventional concrete	up to C53/65
• High Performance Concrete	C53/65 to C90/105
• Ultra High Performance Concrete	C90/105 to C200/230

The creation of Ultra High Performance Concrete is made possible by changing the design of the concrete mix by:

- Improving the homogeneity, by using small sized particles the stress variation decreases. This also reduces the transverse tensile stresses. A more homogeneous material results in a more homogeneous stress distribution and thus in a generally stronger material.
- Increasing the package density, by filling the voids with fine particles which can contribute to the strength.
- Improving the microstructure, by hardening the concrete at higher temperatures and/or by hardening at higher atmospheric pressures.
- Adding steel fibres, this leads to small crack distances and give the material large ductility.
- Reducing the water-cement ratio, this way there are less voids created and filled with water, which increases the material strength.

6.2 Reasons for using UHPC

Advantages

- More slender structures are possible which reduces the weight.
- The very dense material structure results in a high durability and a smaller concrete cover.
- A higher prestressing is possible.
- The stress loss in prestressing steel is less as there is less shrinkage.
- It is possible to construct without steel reinforcement.

Disadvantages

- UHPC with steel fibres cannot be recycled as the steel fibres can hardly be taken out.
- UHPC is more expensive than conventional concrete
- The production capacity of a concrete mixing plant decreases for the production of UHPC as the mixing takes longer and is more complicated.
- The hydration process within UHPC is fast which results in a large heat production. This results in a fast hardening shrinkage during the first days. Variable temperatures during hardening within the concrete result in internal stresses causing cracks. It is therefore important to control the hardening process and protect it from the changing weather conditions. This is particularly important for thick construction elements.
- There is little known about fatigue of the material.

6.3 Mix procedure

The mix design of UHPC is complex. With a low water-cement ratio and many additives the mix is relative dry. This makes it hard to mix all the materials together. By adding superplasticizers the workability of the mix can be ensured. It is important to divide the additives and fillers into doses to the mix and at the right time. This however results in a longer mixing time. The UHPC composition is very sensitive to little variations in the amount of materials and is also influenced by the weather conditions.

The latter has less influence when the mixing takes place in factories. Considering all this it is assumed best to utilize precast UHPC elements instead of in-situ UHPC as this ensures a better quality. However, the utilization of in-situ UHPC is not impossible. Special attention should be paid to the curing of the UHPC because of its very low or even total absence of bleeding. The outer skin and construction joints should be checked and cured to prevent drying out of the concrete causing micro-cracks.

6.4 Design study

Currently there is no Dutch or international code for constructing in UHPC. Hence, in the design study a thesis will be used [2] made by H.J. de Bruijn. This thesis contains a study to UHPC and gives structural design methods for constructing in UHPC. These design methods are on their turn mainly derived from the French recommendations [18]. With these design methods it is supposed to have enough and reliable information to design an elevated railway made from UHPC in the design study.

7. Fibre Reinforced Polymers

References: [9] [17]

Fibre Reinforced Polymer (FRP) is a composite material. This means the combination of two or more materials on a macroscopic scale to form a useful material. By combining fibres with polymer resins a material is created with characteristics that none of the components exhibit independently.

7.1 Reasons for using FRP

Standard properties of FRP composites:

- High strength at low weight
- Good impact, compression, fatigue and electrical properties
- Ability to fabricate massive one-piece mouldings
- Moulding to close dimensional tolerances
- Short installation times

The following additional properties can readily be provided by reinforcement and/or matrix alteration, chemical addition or other formulation, material or fabrication alteration:

- Excellent chemical and corrosion resistance
- High ultraviolet radiation stability
- Good-to-excellent fire hardness
- Good structural integrity
- Good thermal insulation
- Ability to attenuate sound
- Respectable abrasion resistance
- Ready bonding to dissimilar materials
- Medium-to-high productivity rates

The physical, mechanical and cost-effective properties of any reinforced plastic composite can be 'tailored' over a wide range to suffice with the performance specification demanded. This however has the disadvantage that there are few 'standard' composites. Besides, companies which fabricate FRP often keep their product information secret. This has led to few codes for specific applications. The key to a more widespread use of FRP materials is to have manufacturer-independent application codes for civil engineering practice. The problem of the wide variety of materials and possibilities of application could be overcome by their classification in so-called Application Categories, for which in a first step application recommendations could be worked out.

Several other disadvantages of FRP are:

- Poor ductility, particularly when compared with metals and considering those composites that are thermoset-based
- Low stiffness in comparison to many traditional and/or competitive materials
- Temperature is limited, with few exceptions, not above150 °C
- Limited recycling ability even when thermoplastic-based
- Material costs still high

7.2 Materials

FRP consist of load-bearing fibres and a resin matrix in which they are embedded. Whereas the fibres exercise the actual load-bearing function, the polymer matrix essentially has four functions:

- Fixing the fibres in the desired geometrical arrangement
- Transferring the forces to the fibres
- Preventing buckling of the fibres under compression actions
- Protecting the fibres from humidity etc.

The mechanical properties of fibre-polymer bonds are mainly determined by the adhesion and the mechanical compatibility between the fibres and the matrix as well as the angle between the fibres and the direction of loading. In order to obtain a good mechanical interaction between the fibres and the matrix, their parameters must be adjusted to each other.

7.2.1 Reinforcements

Reinforcements are used with resin systems to improve the mechanical properties of cured[2] resin and provide usable components. By far the most important fibre used with epoxy resins is glass fibre, which is supplied in a variety of forms. In recent years high strength carbon fibres and polyaramid fibres are used increasingly in the manufacturing of composite materials for all applications, often in the form of hybrid products where the best features of each constituent are utilized to the full. The high strength and stiffness-to-weight ratios of carbon and polyaramid fibres make them particularly attractive for the manufacture of lightweight structural components. The costs are however far more expensive compared with glass fibres, with polyaramid fibres about 15 and carbon fibres about 40 time the cost of glass fibres. The proportion of reinforcement present in a composite has a major effect on its properties, so does fibre type and fibre orientation. Fibre content is usually expressed in terms of a weight fraction, a volume fraction or a resin/fibre ratio.

7.2.2 Resins

On their own, bundles of parallel fibres are of little use in a load-bearing structure. They may have structural integrity in tension but unless they can be joined, their structural potential cannot be harnessed. Similarly, bundles of fibres are almost useless in shear and compression. Without a means of distributing load across a series of fibre bundles, the material is of no use for structural applications other than rope, which works in cable tension. By 'gluing' bundles of fibres together with resin matrices, materials are made where the strong, stiff fibres are able to carry most of the stress whilst the matrix distributes the external load to all the fibres as well as providing protection and preventing fibre buckling under compressive loads. The most critical region for the load transfer process is the fibre-resin interface. Common applied resins in FRP are:

- Polyester Resins
- Vinyl Ester Resins
- Epoxy Resins

Epoxy resins offer the best mechanical properties for FRP. The costs of epoxies are higher than polyesters but they are very versatile and widely used.

7.2.3 Cores

Sandwich construction is commonly used with composites to increase structural efficiency, with the FRP forming the outer skins and bonded to a variety of core materials.
Materials available as cores are in three forms:

1. Basically lightweight (e.g. balsa wood)
2. Lightweight because foamed
3. Lightweight because honeycombed.

Bridge deck systems and bridge structures made of FRP are often sandwich elements with a core of honeycombs or something alike (see Figure 45 and Figure 46). Honeycombs are formed from in fact any thin-sheet material connected together in a manner that resembles the honeycomb made by bees hence the name. The structural performance is particularly high in direct compression and shear due to the directionality of the shaped form.

[2] Cure: the process of hardening of a thermosetting resin (by cross-linking of the molecular structure), under the influence of heat and/or curing agents.

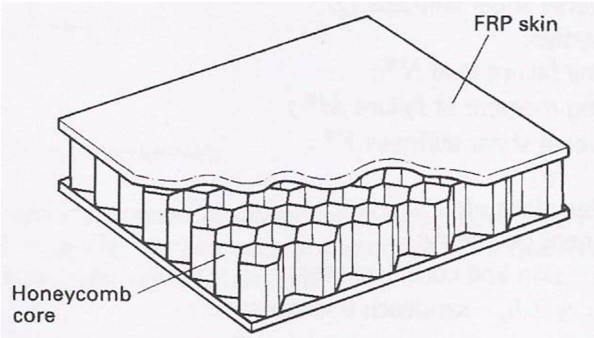

Figure 45: Sandwich panel with honeycomb core

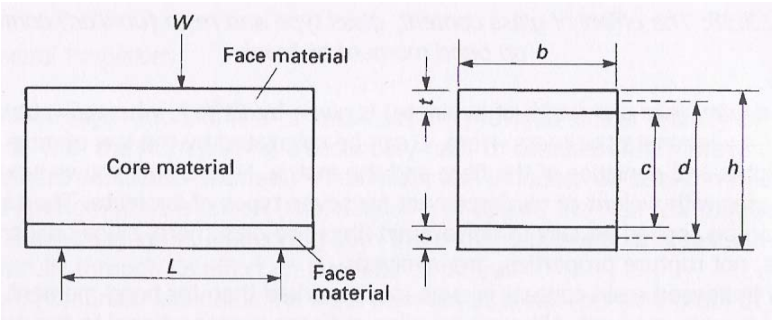

Figure 46: Parameters for sandwich composite calculations

7.3 Manufacturing process

Thermosetting resins are among the simplest of plastic materials to process. All that is necessary is to mix the activator[3], pour into a mould, leave to set and then remove from the mould. An extract reproduction of the mould contours is produced without any need for heat or pressure. The mould can be made from almost any non-porous material. All fibre reinforced polymer composite manufacturing processes contain five elements:

1. Mixing resin and activator
2. Dispensing resin into the mould
3. Curing
4. Positioning reinforcement
5. Impregnating reinforcement with resin

Methods of executing the individual elements can be thought of as ‘techniques’. Each manufacturing process can therefore be considered as an assembly of techniques for executing the five elements. This is an important point because it indicates the large number of processing arrangements which are possible with composites by using different combinations of techniques. All the different combinations will not be described here.

7.4 Bridges

Bridges made of FRP are applied increasingly the last years. Despite the high material costs, the lack of experience with respect to durability and long-term behaviour and the lack of standards, application guidelines and design codes, it becomes gradually more attractive to construct with this material. The bridges made of FRP are often sandwich superstructures and serve as footbridges and smaller highway bridges. Cable stayed and truss bridges made of FRP can also be found but are rarer. In the future it is expected that FRP will become more economical which means a broader application range. It is expected that FRP bridges will then be constructed for more applications.

7.5 Design study

As mentioned before, there is a wide range of FRP producible and there is a lack of standards. In order to design an elevated metro railway made from FRP a thesis is used in the design study [17]: Onderzoek naar composietmaterialen in brugconstructies, which can be translated from Dutch to

[3] Activator: a chemical compound used with a catalyst to permit polymerization at room temperature.

English as: Research to composite materials in bridge structures. This thesis is made by W.D. Schutte and M. Sayed and is executed at the engineering office of Rotterdam Public Works (In Dutch: Ingenieursbureau Gemeentewerken Rotterdam, IGWR). This thesis provides information on FRP and also the InfraCore® concept is analysed. The InfraCore® concept is a combination of FRP and a sandwich construction and is invented by FiberCore Europe. From this concept an arithmetic method is derived to design FRP bridges as a sandwich construction. This arithmetic method is applicable at macro level. The micromechanics are not taken into consideration in this thesis, among other things because FiberCore Europe was not willing to give this information. This thesis should however give enough information to design an elevated railway made from FRP in general. Points of interest are the possibility of delamination[4] and the stiffness of the bridge.

[4] Delamination: splitting, physical separation or loss of bond along the plane of layers of a laminated material.

8. Conclusions, recommendations and continuation

8.1 Conclusions

In search of a suitable application of an elevated metro system in Rotterdam it is concluded that:

- The metro system should have an elevation of 15 metres.
- The elevated railway should span 45 metres.

The decision for these dimensions is extensively elaborated in chapter 5:
A suitable height for an elevated metro system in Rotterdam ranges between 9 and 15 metres. The height of 9 metres is chosen to ensure that people in an average building of 9 metres high can look straight out of the window without seeing the elevated railway. The height of 15 metres follows from a maximum span of 45 metres and a span-to-height ratio of 3 to create a more aesthetical appearance. The reason for a maximum span of 45 metres is twofold: Firstly with this span length it is expected that the metro alignment can follow the street pattern of the city and fits into the proportions of the city. Secondly this is seen as the most economical span as it can be built with in-situ concrete, precast concrete and steel girders. Rotterdam is however not just a city but wants to distinguish itself from other cities and because an elevation of 12 metres becomes more common an elevated metro system in Rotterdam should have an elevation of 15 metres. A higher elevation also creates a more open and lighter area underneath the structure. Moreover, this is more challenging for further elaboration in the design study of the graduation thesis. If the elaboration of the elevated railway with a span of 45 metres turns out to be an appropriate structural design it is still possible to decrease the height.

Because the elevation is less than 30 metres (see chapter 3) this means that:

- Escalators should be utilized as major means of transportation.
- Stations should be provided with stairs in case of emergencies.
- Stations should be provided with elevators to transfer the disabled people.

Further conclusions are:

- The alignment of the metro system should be bundled with other infrastructure as much as possible to decrease the hindrance and make the implementation of the project easier.
- The stations should be made transparent as this creates a better social and secured environment.

8.2 Recommendations

Some recommendations are made concerning the application of an elevated metro system during the literature and preliminary study. These recommendations are described below and serve as ideas which can be implemented into the design. In the design study of this graduation thesis, these recommendations are however not taken into account.

8.2.1 Emergency circumstances

If the elevation of the metro station becomes too high this can cause problems for the evacuation time. When it takes too long to take the stairs downwards another option should be available. An idea for this problem is to connect the elevated station with surrounding buildings by means of skybridges (overhead pedestrian walkways). This will reduce the evacuation time considerably.

Emergency circumstances can also occur outside the metro stations at the elevated railway. When the distance between two stations becomes too large it could lead to an unacceptable distance to cover for the passengers. A solution could be to provide the network with extra emergency staircases between these stations.

8.2.2 Vertical city

When stations are situated close to other medium- or high-rise buildings it could be an option to connect them by means of skybridges (overhead pedestrian walkways). This can create, if applied between more buildings in that area, some kind of second level for pedestrian traffic. With this multiple land use and two levels it can set the trend towards the vertical city with multiple levels of horizontal traffic. An option could also be to integrate the concourse inside the buildings and connect the platforms with skybridges. An even more sophisticated option would be to build the whole station within a building with the elevated railway passing through.

8.2.3 Aesthetics/green

Aesthetics is an important issue for this metro system as with an elevation of 15 metres it will also serves as a landmark. The structure should therefore have an attractive appearance. This can be achieved by many ways. One way is however to cover the columns with ivy. Plants often create a pleasurable effect and they bring more green into the city streets. Besides the C02 emission in the city becomes less.

8.2.4 Integrated walkway/cycle way

An idea could be to integrate a pedestrian walkway or cycle way with the elevated metro system (see Figure 21). This allows a fast and safe movement for pedestrians and cyclists without hindrance from other means of transport. With the walkway/cycle way beneath the railway it can also offer protection against the rain (depending of the wind). An elevated cycle way could be the solution for Rotterdam to create a city which is more attractive for cyclist. Major disadvantage is that it will enlarge the visual barrier.

8.3 Continuation

The conclusions considering the dimensions of the elevated metro structure together with useful information from chapter 4, 6 and 7 from the literature and preliminary study will be taken along in the design study. The design study concerns the structural design of the elevated metro system. Different concepts will be analysed for the elevated railway structure made of conventional concrete and Ultra High Performance Concrete (UHPC) and the best concept will be further elaborated. Besides a global design for the elevated railway structure made of Fibre Reinforced Polymers (FRP) will be made.

- For the design of the elevated railway made from conventional concrete in the design study the Eurocode 2: “Design of concrete structures” will be used.

- For the design of the elevated railway made from UHPC in the design study a thesis will be used [2] made by H.J. de Bruijn. This thesis contains a study of UHPC and gives structural design methods for constructing in UHPC. These design methods are mainly derived from the French recommendations [18].

- For the design of the elevated railway made from FRP in the design study a thesis will be used [17]: Onderzoek naar composietmaterialen in brugconstructies, which can be translated from Dutch to English as: Research to composite materials in bridge structures. This thesis is made by W.D. Schutte and M. Sayed and is executed at the engineering office of Rotterdam Public Works.

Finally the three designs will be compared with each other which should give a clear view on the differences in dimensions and normative structural verifications between the application of conventional concrete, Ultra High Performance Concrete and Fibre Reinforced Polymers.

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Appendix 1: Vancouver SkyTrain

History
In 1980 the need for rapid transit was great but till then the municipal government could not fund the construction of such a system. The Expo 86 held in Vancouver made it possible to fund the construction of a metro system by the provincial and federal government. The fair's theme was: "Transportation and Communication: World in Motion – World in Touch". The SkyTrain was chosen to showcase the fair's theme. The SkyTrain began operating on December 11, 1985 and began carrying passengers in January 1986. Since the SkyTrain began, the overall population of the service area rose enormously which made it necessary to expand the Expo line and even create two new lines: the Millennium line (opened in 2002) and the Canada line (opened in 2009). Both lines were completed under budget. The Expo, Millennium and Canada Line were built on a budget of respectively $854 million (1986 dollars), $1.2 billion and $1.9 billion dollars. The Canada line was also built to strengthen the planned bid for the 2010 Winter Olympics and opened 15 weeks ahead of schedule. The SkyTrain has had a significant impact on the development of areas in which stations are located. The corridor that the SkyTrain runs through became the main development axis of Vancouver with a notably denser urban form after the opening of the SkyTrain. Development densities along the SkyTrain route have changed especially as a result of the rezoning plans of the municipalities. These plans increased the densities at station areas, and encouraged office and retail centres at stations. Some of the SkyTrain stations became the 'new town centres' as proposed in the metropolitan development plan. The Canada line is operationally independent from the Expo and Millennium lines and uses rolling stock that is incompatible with other lines, but is considered part of the SkyTrain network.

A survey in 1998 conducted by Canadian Facts for the Rapid Transit system showed that:
- 61% of residents in Greater Vancouver were "more likely" to support the construction of SkyTrain rather than ground-level Light Rail Transit;
- 71% said that "even though SkyTrain is more expensive to build, it is better than ground LRT";
- 69% felt that SkyTrain would have the largest impact on traffic reduction followed by either transit links (54%) rapid buses/dedicated lanes such as the ones used for the B-Line bus routes (40%) and less expensive LRT lines (32%);
- 63% of respondents said that SkyTrain is the best mode of transportation, followed by the bus system (24%), the West Coast Express (3%) and the SeaBus (1%);

Future extensions
In 2009, the provincial government of British Columbia announced the following future expansions to the SkyTrain network (see Table 3):

Project Name	Line	Date of completion	Section	Length
Evergreen Line	Evergreen	2014	Lougheed Mall to Douglas College	11 km
UBC Extension	Millennium	2020	VCC-Clark to Fleetwood	12,6 km
Fleetwood Extension	Expo	2020	King George to Fleetwood	6 km
King George Extension	Expo	2030	King George to 64th Avenue	7 km
Langley Extension	Expo	2030	Fleetwood to Langley Centre	7 km

Table 3: Future expansions of the Vancouver SkyTrain

Evergreen Line

The Evergreen Line will be the fourth line of the SkyTrain network and has the colour green (see Figure 47). The line will connect Lougheed Town Centre Station on the Millennium Line in Burnaby to Douglas College in Port Moody. The expected cost of the new line is $1.4 billion dollars and it is integrated with the Millennium Line. The Evergreen Line will run mostly on elevated tracks, but also has underground and at-grade parts.

UBC Extension

The UBC Extension is an extension of the Millennium Line from VCC-Clark station towards the University of British Columbia (see Figure 47). The line would replace the regions busiest bus routes, where over 100,000 trips are already made on a daily basis. The line would also include an interchange with the Canada Line and is estimated to cost $2.8 billion.

The Expo Line extensions

The three extensions of the Expo Line will extend to the south (King George Extension) and to the southeast (Fleetwood Extension + Langley Extension) (see Figure 47). The southeast extension will be built in two phases. The total cost of these three extensions is expected to be $3.1 billion.

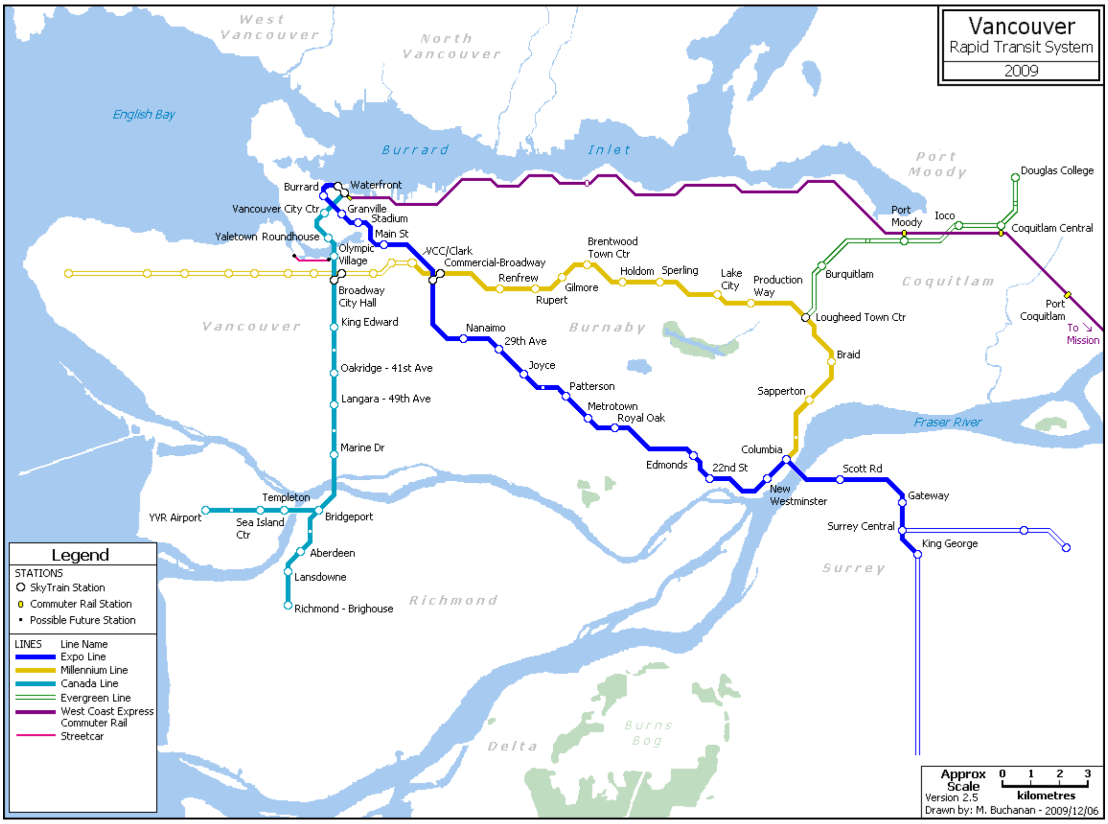


Figure 47: The Vancouver Rapid Transit System with its extensions

Appendix 2: Bangkok Mass Transit System

History

In an attempt to fight the chronic traffic congestion in Bangkok, the Thai Government focused on increasing road and expressway infrastructure. This however had not the desired impact as the number of cars on the road increased dramatically. In the late 20^{th} century, they therefore initiated studies on mass transit systems in an effort to provide a long-term solution to road congestion. This resulted in the BTS SkyTrain, which opened on December 5, 1999. The Thai contractor Italian Thai Development built the system and Siemens was supplier of the railway technology. From contract signature to the operation of the first service trains took four-and-a-half years, a remarkably short time given the scale of the infrastructure works, and the busy nature of the city amidst which they worked.
The system was handed over a month ahead of schedule.

Rolling stock

The electrification system of the BTS Skytrain is not only high-tech but tested and proven to have no environmental impact. Some important highlights of its operating system are given below:

- Seamlessly welded tracks minimize noise of passing trains.
- The track support system designed for maximum shock absorption.
- The wheel suspension system absorbs vibrations and decreases noise caused by friction between wheels and track.
- The curved sections of the tracks have a gauge that's slightly wider from the rest of the tracks to decrease friction between wheels and track and are also lubricated to minimize noise.
- An electrical brake system is used. This allows the train motor to be transformed into an electrical generator that works to stop the train and feeds electricity back into the system. Mechanical brakes are applied when the train is running at speeds lower than 8 km per hour. The mechanical disc brake uses a highly efficient anti-sliding system. The tracks are bordered by a noise barrier not only to decrease noise levels but also improve the system's overall aesthetic quality.

Future extensions

In order to improve the infrastructure even more, extension plans are proposed and adopted for the coming years. The extension plans for both lines are planned in two phases:

Phase 1

On Nut – Bearing – 5.2 km.	Under construction, to open in late 2011.
Saphan Taksin – Wong Wian Yai – 2.2 km.	Completed, opened on 15 May 2009.
Mo Chit – Saphan Mai – 11.4 km.	Planned.

Phase 2

Bearing – Samut Prakan – 10.6 km.	Planned.
Wongwian Yai – Bang Wa – 5.3 km.	Planned for early 2011.
National Stadium – Phran Nok – 6.8 km.	Planned.
Saphan Mai – Lam Lukka – 14 km.	Planned.

The master plan for Bangkok's mass transit system is given in Figure 48. On this map the proposed extensions of the SkyTrain network are shown (the light and dark green line). The extension plans for the underground metro system (Bangkok MRTA) and the railway network (State Railway of Thailand, SRT) are also depicted here. The master plan shows a large mass transit network by combining the three mass transit systems. In the future the execution of this master plan should result in an optimal infrastructure network creating an accessible city.

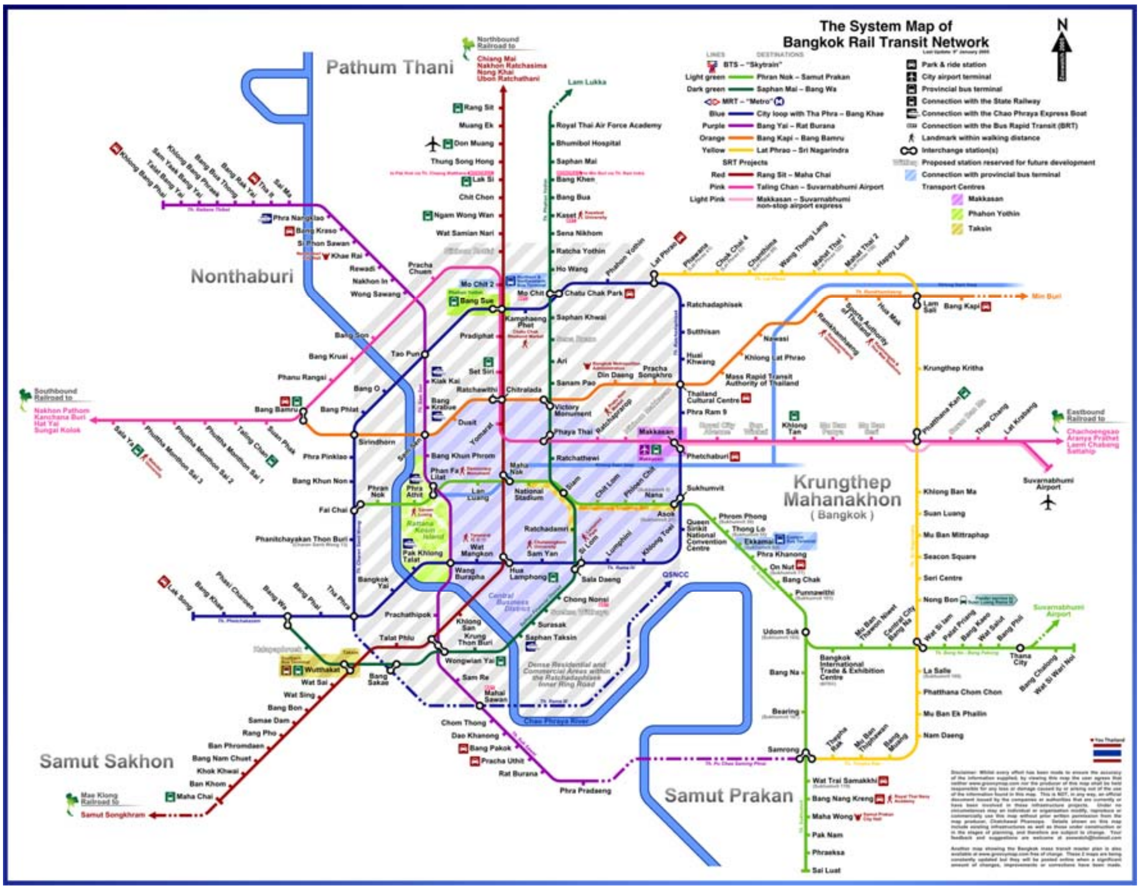


Figure 48: Mass transit master plan of Bangkok

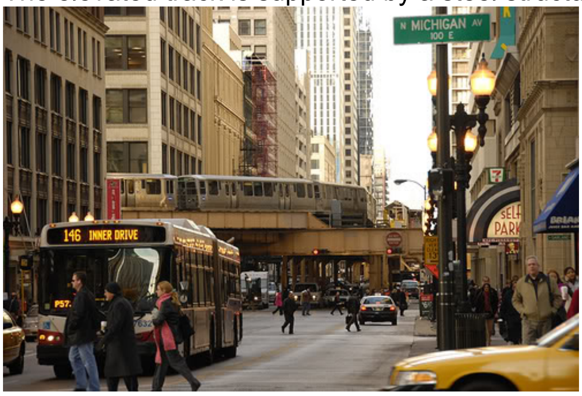
Appendix 3: More elevated metro systems

Chicago “L”

References: [i28] [i38] [i42]

Date opened	1892
Number of lines	8
Number of stations	144
Electrification	third rail
Track gauge	1.435 m
System length	165 km
Elevated track length	57.6 km (most of it in the city centre)

The elevated track is supported by a steel structure which is about 6 metres high.



Dubai Metro

References: [i3] [i8] [i28] [i37]

Date opened	09/09/2009
Number of lines	1 partly under construction (red line), 1 under construction (green line) and 2 proposed (purple and blue line)
Number of stations	10 (37 stations under construction)
Electrification	third rail
Track gauge	1.435 m
System length	52 km (red line)
Elevated track length	47.4 km (4.7 km underground in the city centre)

Once the 22.5 km green line opens, the Dubai Metro will overtake the title of longest automated metro network from the Vancouver SkyTrain.

Delhi Metro

References: [i21] [i28] [i34]

Date opened	2002
Number of lines	3 (phase 1)
Number of stations	59 (phase 1)
Electrification	overhead wire
Track gauge	1.676 m
System length	65 km (phase 1)
Elevated track length	50 km (phase 1)
Planned system length	241 km (2021)

Miami Metrorail

References: [i25] [i28] [i35]

Date opened	1984
Number of lines	1
Number of stations	22
Electrification	third rail
Track gauge	1.435 m
System length	36 km
Elevated track length	34 km

Wuppertal Schwebebahn

References: [i33] [i38]

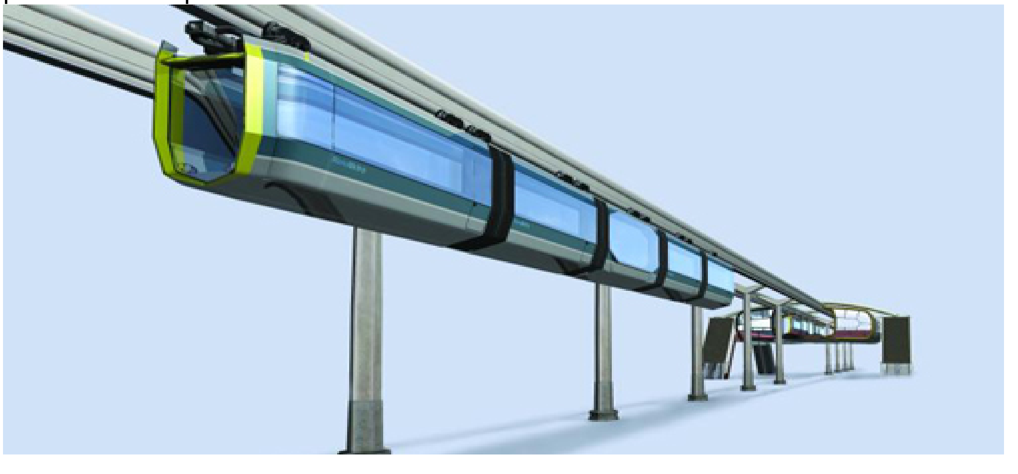
Date opened	1901
Number of lines	1
Number of stations	20
Transit type	suspended monorail
Elevated system length	13.3 km

The Al Mashaaer Al Mugaddassah Metro Line (Mecca, Saudi Arabia)

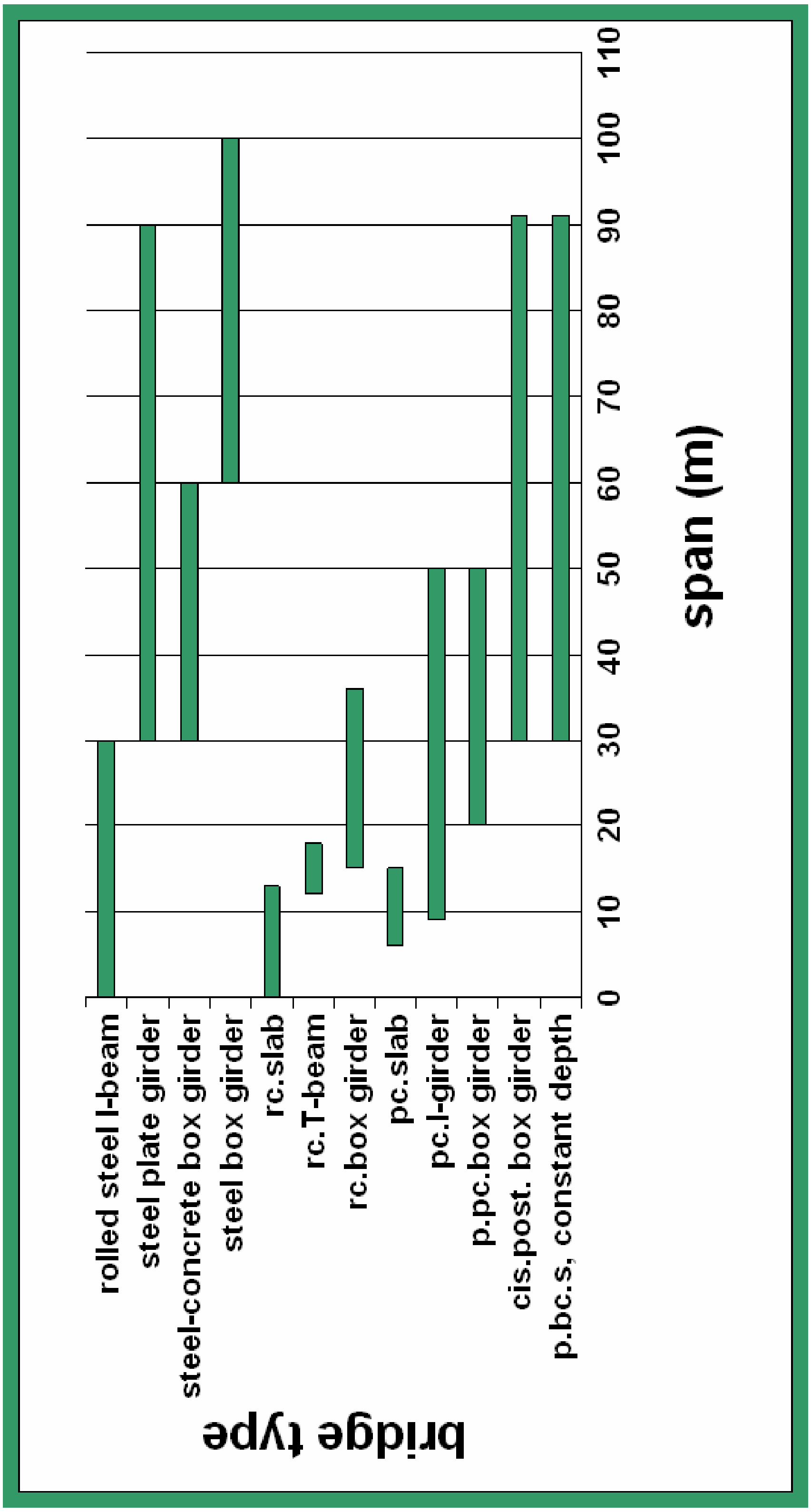
References: [i28]

Opening date	2011
Transit type	suspended monorail
Track elevation	8 to 10 metres
Number of lines	5
System length	20 km

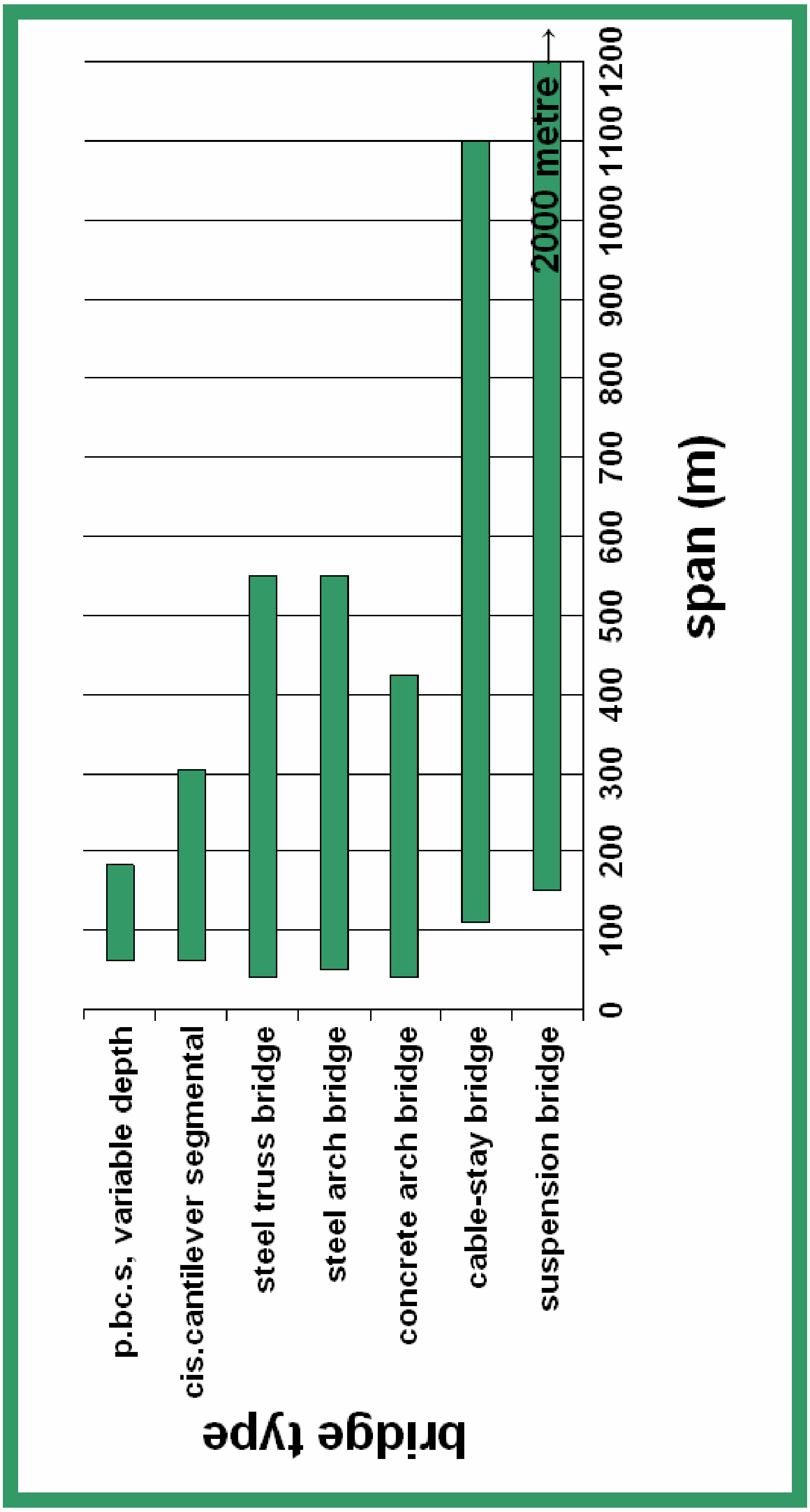
The monorail will run on a powerful superstructure made of steel railroads supported by solid concrete pillars made of prefabricated steel masts and beams.



Appendix 4: Span range for bridge types



Graph 1: Span ranges for small-span bridge types



Graph 2: Span ranges for long-span bridge types

Explanation abbreviations:

- rc = reinforced concrete
- pc = prestressed concrete
- p = precast
- cis = cast in-situ
- post = post tensioned
- bc = balanced cantilever
- s = segmental