

# The Hybrid Guideway Girder Development and first application in Shanghai

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## Keywords

China, Hybrid Guideway Girder, Shanghai, structural engineering, Transrapid

## Abstract

The first commercial use of the Transrapid will be realized on a 30 km track in the People's Republic of China. At present, the Chinese are building a link between Pudong Airport and Long Yang Road Station in the outskirts of Shanghai. The technology required to build this hybrid guideway is provided by the German TGC.

This paper reports on the development of this new guideway type for the Transrapid maglev system. Moreover, the Shanghai track will serve as an example to illustrate the technical and economic advantages of the hybrid guideway concept.

## 1 Introduction

After the track Berlin – Hamburg had been cancelled, the future of the Transrapid was called into question. Without a first longer distance track it seemed to be difficult to offer and sell the system to prospective customers. However, in the year 2000 the People's Republic of China was seriously interested in the use of the Transrapid in China.

For the first Chinese Transrapid they chose the track between the new Pudong airport and Long Yang Road Station in the outskirts of Shanghai. At this distance of about 30 km the use of the Transrapid will be tested for long-distance traffic. Upon this track, the newly-developed Hybrid Guideway Girder will be used.

Compared to traditionally-produced constructions, which mainly consist of one single building material, i.e. of wood, steel or concrete, the future lies more and more in hybrid constructions. Hybrid structures are composed of different materials co-operating in a positive way. In contrast to pure steel and concrete constructions [1], hybrid constructions offer technical and economic advantages. The Normandy Bridge [2], for example, shows a hybrid superstructure with a steel superstructure in the center area of the main span and a concrete superstructure in the areas close to the pylon and the other parts of the bridge. Due to this construction, the total structure proves to be economically interesting.

As far as the Transrapid guideway is concerned, the technology is provided by the German syndicate TGC (Transrapid Guideway Consulting Group). TGC consists of the engineer's office CBP (Cronauer Beratung Planung) and two construction companies.

In the following, the development of the Hybrid Guideway Girder will be described. The main innovation about it consists in the optimal choice and combination of materials, which are able to meet

the various demands [3]. The construction is based on the technical and system-oriented demands for Transrapid guideways.

In this context, the process of development will be described from the basic idea to the actual use of the new girder type. The essential technological and economic advantages of the Hybrid Girder will be explained and compared with the competing types of guideway girders consisting entirely of either steel or concrete.

## 2 Frame-work conditions for guideway girder systems of the Transrapid

In comparison with guideways of conventional wheel-rail-systems the Transrapid guideway is of utmost importance for the overall systems. For the first time, the drive becomes a component of the guideway instead of the vehicle itself.

The nocontact system for support, guidance and propulsion of the Transrapid uses a long-stator linear motor. It is based on the principle of electromagnetic levitation. The long-stator linear motor could be compared to an electric motor cut open and rolled out along the guideway. Instead of a magnetic rotating field the linear motor produces an electromagnetic travelling field which moves along the track. A highly reliable electronic control system ensures that the train always levitates at a constant distance of 10 mm from the guideway. By reversing the magnetic field, the vehicle can accelerate and brake without contact. In contrast to the traditional traction principle of conventional traffic systems, the primary part of the traction system, the so-called stator packs with their windings, are installed at the guideway. The vehicle requires precise positioning of the operational components built into the track – e.g. stator packs and guidance rails – which allow but marginal tolerances for manufacturing and assembly.

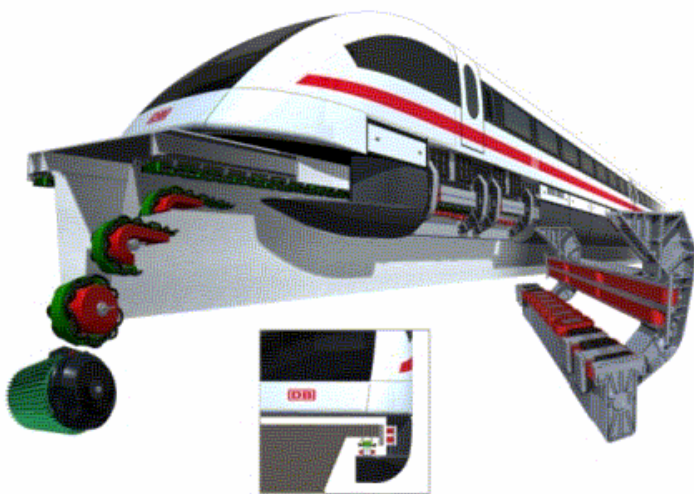


Fig 1: Levitation and propulsion system of Transrapid [4]

### 2.1 System-technical basics

The system-technical demands for the guideway can be derived from the fact that the vehicle levitates in a design distance of approximately 10 mm to its guideway, even at speeds up to 500 km/h:

- least permissible tolerance in the area of the functional elements
- least permissible deflections
- precise geometrical demands caused by the guideway covering vehicle

These demands are harder to meet than those arising from the carrying function. They are a challenge to every engineer.

## 2.2 Permissible deflections and natural frequencies

In vertical direction, the permissible deflections under live load amount to only  $l_{ys}/4800$  and by the maximum vertical temperature gradient to  $l_{ys}/8000$ . The specification prescribes that a temperature gradient of 22 K ( $t_{top} - t_{bottom}$ ) has to be applied for the calculation. This figure exceeds the requirements for usual bridge constructions by far.

The permissible deflections in horizontal direction caused by live loads or horizontal temperature gradients ( $t_{left} - t_{right}$ ) are limited in a similarly stringent way, too.

In addition, the gaps between the girder ends have to be checked with regard to their width in longitudinal direction. The permissible offsets are to be kept in the stator-plane, sliding-plane and guidance-rail-plane, too.

Furthermore, the first natural mode of the girder represents an essential parameter for the design. The calculation criteria concerning the frequencies have their basis in [5]. If the frequency criteria are kept, resonance of the superstructure can be avoided while the train crosses the girder.

Figure 2 shows the result of a dynamic calculation of the girder. Demands concerning the girder stiffness can be derived from the proportional cohesion between the natural frequency, stiffness and masses of the girder.

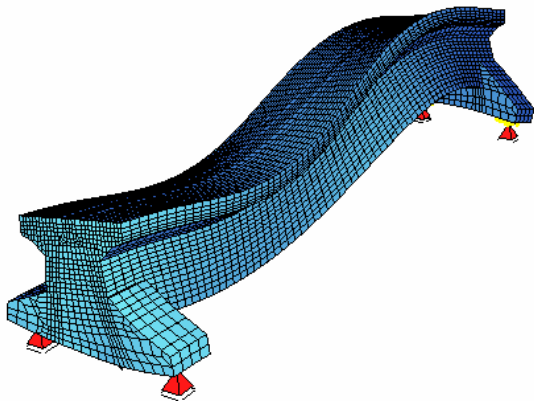


Fig 2: Natural mode plot

## 3 Previous guideway girder types

Two basic types of guideways can be distinguished, namely the so called plate guideway, which can be arranged on ground level or on special buildings, and the so called guideway consisting of separate girders. As the plate guideway is monolithically connected with the foundation, settlement differences can't be balanced as easily as by the use of discretely supported girders. This means that plate guideways bring about a substantial disadvantage, especially if they are placed upon a soil liable to subsidence. That is why, by opinion of the authors, every guideway should be implemented with discretely supported girders.

The track between Berlin and Hamburg demanded spans of 31 m with a construction height of 2 m (type I) as well as spans of 12,4 m and a construction height of 1 m (type II). Regardless of the material chosen, these geometric conditions and the great demands concerning the technical facts mentioned above can only be met by the use of double span girders [6]. Caused by the statical system as a double span girder is the production as well as transportation and installation extremely complicated and thus expensive. In relation to these great serviceability requirements, the proofs of design resistance are of less importance.

At this point, it might be useful to look at previous pure steel and concrete girders, even if these guideway types have already been sufficiently discussed in literature specializing in this field (see [4], [7], [8], [9] and [10]).

### 3.1 Pure steel guideway girders

In the sectional drawing, the steel girder shows a trapezoid box tapering downwards. The whole girder geometrically follows the space curve, which causes a complex and costly manufacturing process.

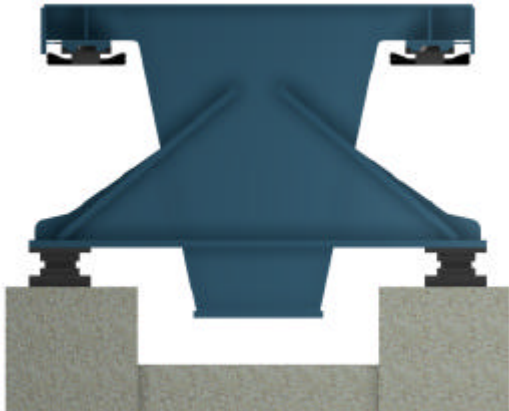


Fig 3: Pure steel guideway girder type I

In addition to its high production costs the steel girder shows the following disadvantages:

- higher sound emission, compared to concrete girders
- relatively low stiffness in vertical direction
- high temperature gradients ( $t_{\text{top}} - t_{\text{bottom}}$ ) or ( $t_{\text{left}} - t_{\text{right}}$ )

With regard to the system specifications, the two last mentioned aspects steel girders can only be build as double span systems.

### 3.2 Pure concrete guideway girders

The concrete girder, type I with a span of 31 m, shows a box-shaped cross section with a construction height of 2 m. The bottom boom is roughly shaped like a semicircle (s. [4] or [8]). The construction with pre-stressed concrete proves advantageous in regard to its insensitivity to girder oscillations. Even in the case of state levitation – a situation critical to oscillation – the high masses and the good damping qualities of the concrete are apt to prevent harmful girder oscillations.

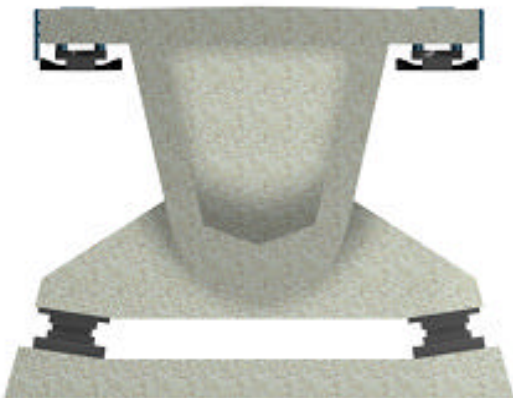


Fig 4: Pure concrete guideway girder type I

Despite various positive aspects of concrete, it didn't, however, prove profitable to attach the functional components by means of grout based on cement. The grouting material was not durable enough and caused high restoration expenses.

## 4 Development of the Hybrid Guideway Girder

The disadvantages of the two girder types described above led to the development of a new girder type. This new girder was to unite the advantages of the existing constructions. The new patent was called the Hybrid Guideway Girder.

### 4.1 Optimal material combination and modular construction

When the hybrid girder was developed, the basic idea was to combine different building materials in order to profit from the advantages of the respective material. At the same time, specific disadvantages of each building material could be avoided.



Fig.5: Principle of the Hybrid Guideway Girder  
concrete/ bracket/ function unit girder

While a pre-stressed concrete girder is apt to carry loads most effectively, the steel construction perfectly meets the system-specific demands on exactness, especially in the functional areas. Moreover, the newly-developed Hybrid Guideway Girder unites the three important elements of the Transrapid, sliding-rail, guidance-rail and stator-pack-fastening to a modular function unit.

#### 4.1.1 Modular function unit girder

Another essential innovation is the application of a module construction for the function unit girders. The function unit girder is produced with a module length of approximately 3,10 m according to the triple system length of the stator packs. Except for a few special modules, the modular function unit girders are all identical. This system makes possible a serial production as well as precision work to the finest tolerances ever reached in the building industry.

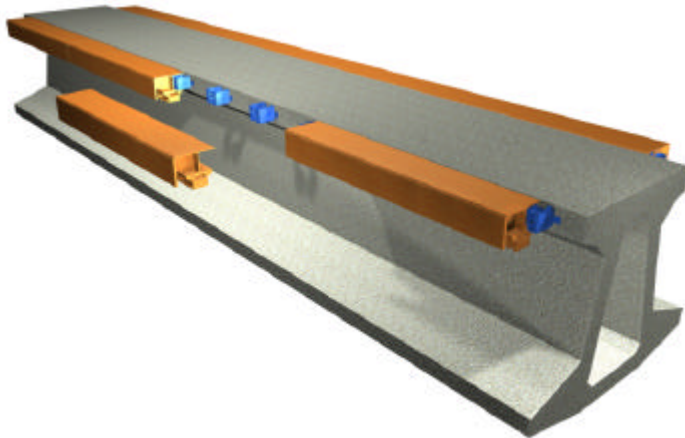


Fig. 6: Modular concept

#### 4.1.2 Brackets as connecting element

Being the connecting element between the main structure (precast pre-stressed concrete girders) and the function unit girders (welded steel structure), the brackets had to be newly designed and checked with regard to their usability.

The brackets transfer the loads from the functional unit girders into the pre-stressed cross section of the main girder. A redundant system of bolts and screws is used here.

Design and construction of the brackets were selected in numerous preliminary tests. As far as the material is concerned, the development lead from welded steel to cast iron. In the following, static calculations using the FE-method, as well as a series of experiments in the form of bench tests, helped to optimize the shape.

#### 4.1.3 Cross section and statical system of the main girder

The pre-stressed concrete girder is produced in precasting works as either a single or a double span girder. Prefabricated girders of pre-stressed concrete prove to be advantageous because they can be produced in a great variety of shapes and statical systems.

The girder is pre-stressed by centric or balanced pretensioning. In addition, tendons with a post-tensioning in the form of garlands help to shape the concrete girder. After production, the girder is stored, so that the deformations of early creep and shrinkage fade away.

Then, a computer-controlled machine machines the brackets, compares its actual geometry to the role-model and levels out the difference by milling and drilling. This is the only way to guarantee the exactness required in the functional areas along the girder. As a result, the inaccuracy in z-direction amounts to only 1 mm maximum.

One of the economic advantages of the hybrid system lies in the fact that the huge dimensions of former constructions which had to be machined have been replaced by the small areas of the brackets which can be easily machined.

#### 4.2 Statical calculation and dynamical analysis

The whole hybrid girder as well as its single components were subjects of statical calculations and dynamical analyses. All modern techniques, i.e. the Finite Element Method, were used in order to calculate the bearing behavior of the girder.

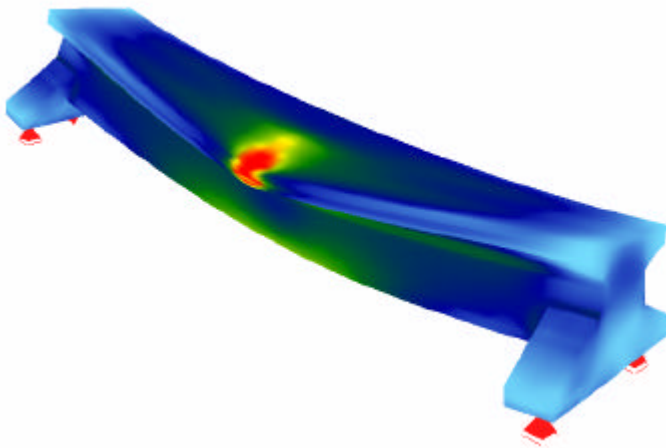


Fig. 7: Statical and dynamical calculation model

It has to be mentioned that not only the bearing capacity (ultimate limit state) of the girder had to be checked. As comfort is of great importance to the Transrapid, the girder's behavior (e.g. deformation) under live load had to be verified and proved too (serviceability limit state). Of course, the fine tolerances given by the Transrapid design code had to be respected.

The brackets have been designed on the basis of FEM-calculation, in an iterative process. They have to meet contrasting demands. In order to minimize the stresses by constraints, the brackets have to be relatively soft. On the other hand, the brackets need to be resistant enough to minimize deflections by live loads. The newly developed brackets are apt to combine these criteria in a perfect way.

## 5 Test of the Hybrid Girder

In order to generally use this new girder type for the Transrapid Guideway, it is and was necessary to go through a detailed testing procedure. The series of tests can be roughly divided into three steps:

- during the development: lab tests of construction components
- during the testing phase: prototype girders
- during the commercial use: selective long term measurements

### 5.1 Lab tests for construction components

In addition to the theoretical verification, the essential construction components were checked by the means of bench tests in order to confirm the computational results. Special attention was paid to the brackets and to their anchorage in the concrete.

The combination of concrete and brackets was checked for fatigue and ultimate resistance, in a static test concerning the bearing capacity as well as in a dynamic test of fatigue (continuous vibration test). For this purpose, a three dimensional test equipment was used at the IABG in Munich. Furthermore, tests were run with naked brackets, i.e. brackets without surrounding concrete, in order to test their anchorage for fatigue. The aim of these experiments and detail improvements was to build components which stayed below the constant amplitude fatigue limit, no matter which of the relevant loads rested upon them.

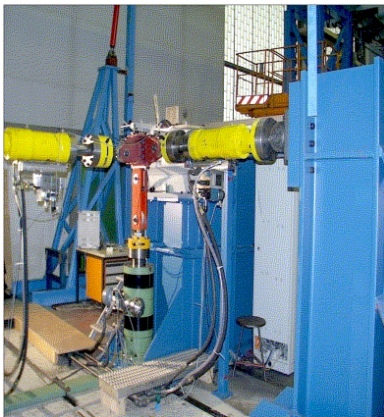


Fig. 8: Test specimen and triaxial testing machine

In addition, the first tests were carried out to investigate the creep and shrinkage behavior of the concrete used. After all these tests, calculation and reality seem to really match quite well.

### 5.2 Prototype girder

Even in 1997, the first hybrid prototype girders were produced. These girders already combine all essential characteristic features of the hybrid concept:

- pre-stressed concrete main girder
- brackets as a connecting element
- modular function unit girders



Fig. 9: Prototype girder at the site

In 1999, a girder with a total length of 2 x 31 m and a construction height of 2 m, comparable to the girders of the track Berlin – Hamburg described before, was installed at the existing Transrapid testing facility (TVE) in Emsland.

### 5.2.1 Prefabrication of the pre-stressed concrete girder

The production of the concrete girder is based on stationary formwork systems with automatically adjustable formwork components. The different production steps run according to a specified schedule. The production process is based on the following steps:

- reinforcement prefabrication within precise reinforcement templates
- installation and adjustment of the brackets
- installation of the pre-stressing reinforcement
- insertion of the inside formwork
- concreting, compacting and smoothing of the girder
- cutting of the pre-stressing wires, after concrete setting
- transportation of the girders for storage by portal cranes
- controlled creep and shrinkage behavior during storage

In order to guarantee the girder's high qualities, all manufacturing processes are constantly supervised by means of a permanent and certified quality management.

### 5.2.2 Prefabrication of the modular function unit girders

The function unit girders are produced automatically as follows:

- cut of the raw materials by computer-controlled saw and flame cutting machines
- shot blasting of the single parts in continuous shot blasting machines
- automatical assembly by means of welding and assembly robots
- application of the quadruple corrosion prevention in a varnish and drying facility

### 5.2.3 Hybrid Girder assembly at site

Before the final assembly the function unit girders are equipped with the stator packs. After that they are installed at the girder. Portal cranes move the girder into a hall for final assembly, where the girder gets its final tensioning, too.

Then the girder is positioned between two linearly working machines, namely CNC-controlled measuring as well as electric drilling and milling machines. These machines work the contact areas of the brackets in their final position on the track, corresponding to the geometrical demands.

Finally, the prefabricated function unit girders are precisely mounted at the brackets.

This way of manufacturing, in connection with a controlled serial production of clearly separated elements, is able to guarantee the tolerances given. The separate components of the girder prove advantageous not only due to their interchangeability but also in terms of simultaneous maintenance and corrosion prevention.

#### **5.2.4 Fabrication, transportation and implementation of the prototype girder in the TVE**

In contrast to the double span girder with a length of 62 m which is usually installed at the application track, the prototype girder at the TVE was produced in two pieces with a length of 31 m each. One reason for that was the problem of moving a pre-stressed concrete girder with a length of 62 m from the manufacturing place in Neumarkt (Germany) to the Emsland, a distance of about 700 km.

After manufacturing, the two girder parts, with their dry adhesion joints, were pressed together by means of post-tensioning tendons. As soon as the deformations caused by creep and shrinkage had calmed down, the unfinished parts of the pre-stressed concrete girder were moved to a hall and kept under temperature control. During this stage of storage under clearly defined conditions, the girders were prepared for final assembly. In the course of this procedure, they were machined and completely equipped, disassembled again into two halves and transported to the Emsland.

At the testing facility, the two parts of the guideway girder were positioned upon jacks and tensioned together again. After that, the prototype girder was put into its intended position upon the existing sub-structures, by means of two heavy weight cranes. Finally, the fine positioning was done and the bearing sockets were poured.

Since its installation in September 1999, the girder is kept under constant observation and permanent control. In the course of a measurement program, the deflections and strains have been determined, as well as the stresses due to live load and temperature.

The test data were compared with the computational results. After two years of testing, the hybrid guideway girder proves to be within the limits of tolerance. This innovative girder therefore confirms all the previous theoretical calculations and demonstrates its readiness for use. The outstanding and most important advantages of the Hybrid Girder compared to all other guideway systems are:

- cost-effective production
- low maintenance costs
- high durability
- low acoustic emission

#### **5.2.5 Measurement**

The completely equipped girder was installed at the TVE and the tests started in accordance with given instructions and measurement programs. The purpose of the twelve months' test phase is to verify the underlying assumptions for loads and weights, to measure the acting forces, which have been determined theoretically by static and dynamic calculations, and to check and confirm the serviceability and safety requirements.

In the course of examination, the load effects upon the girder, caused by the vehicle and the environment, are determined by static and dynamic measurements. As an example, fig. 10 shows the measured maximum temperature difference between upper and bottom boom. This maximal measured temperature difference is only approximately one third of the temperature difference assumed in the system specifications which had been the basis of the theoretical calculations and design.

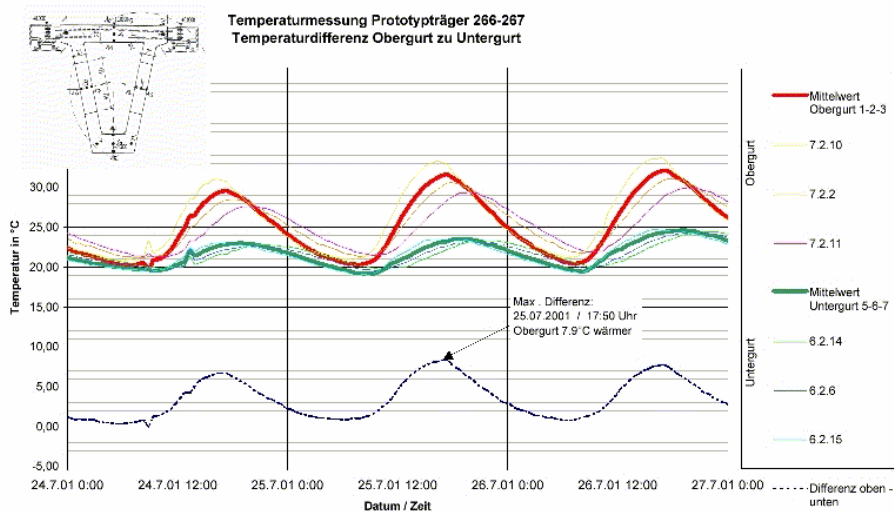


Fig. 10: Measurement results of the vertical temperature gradient

### 5.3 Long-term measurement

The equipment of long-term measurements roughly corresponds to that of the prototype girder. Long-term measurements will be carried out in selected parts of the commercial track. The results help to control basic assumptions and to advance the development of the guideway. They also serve for the conservation of data.



Fig. 11: Transrapid TR07 on the Hybrid Girder at TVE

## 6 Shanghai – the first commercial use of the Hybrid Guideway Girders

Originally, the first commercial track should have been built between Berlin and Hamburg in Germany. However, this project was cancelled in 2000 for monetary reasons. This is why the first Transrapid track is now located in the People's Republic of China.

The opening ceremony, which is of high political importance, will take place in January 2003. Then, at the end of 2003, standard traffic will start upon the two-lane track between Pudong airport and the city of Shanghai. At this distance of 30 km, the top speed will amount to approximately 430 km/h, which means a driving time of about 8 minutes.

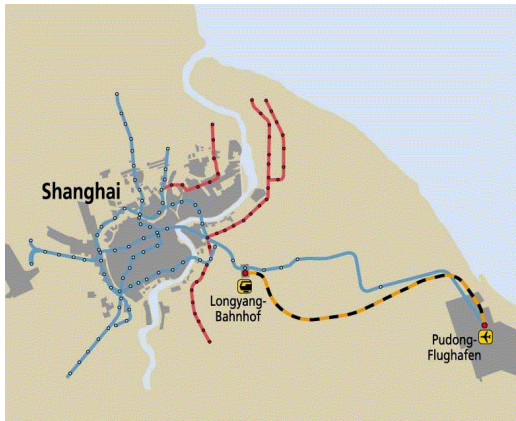


Fig. 12: Map of the Transrapid in Shanghai

In autumn 2000, the first contact with the prospective customers was made in Germany. Having tested the previously-known guideway superstructures with regard to technical and economic facts, the Chinese decided to apply the Hybrid Guideway Girder.

In November and December 2000, the engineer's office CBP and the building company Max Bögl developed a new hybrid guideway girder in the course of a feasibility study. In this context, the maximum standard span was reduced from 31 m to 25 m, in order to optimize the economic viability of the girder. At the same time, the construction height of the girder was raised by 20 cm. The shape of the cross section was optimized with regard to stiffness, deflections, acoustics and temperature gradients.

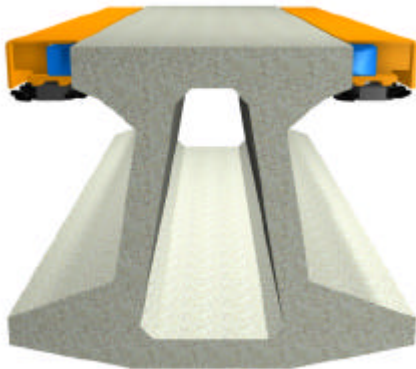


Fig. 13: Cross section of the Hybrid Guideway Girder, type I, developed for Shanghai (CBP)

Directly after the conclusion of the contract in 2001, Chinese engineers came to Germany in order to be introduced to the technology and the methods of construction of the Hybrid Guideway Girder. The ten-week-training included the following topics:

- foundation varieties
- substructures of the guideway
- design of the Hybrid Guideway Girder
- fabrication of the Hybrid Guideway Girder

The engineer's office CBP gave a report on the calculation of hybrid girders. The girder's production was explained by the Max Bögl Company at their production plant in Neumarkt. In the context of this training, design and layout of a production plant for hybrid girders were worked out, too.



Fig. 14: Production plant for Hybrid Guideway Girders in Shanghai

Within a year, all foundations have been built with cast-in-situ concrete. The railway stations at the airport and at the subway station are almost finished, too. This progress in production was only made possible by shift working around the clock, seven days a week. During the peak period, 10 000 construction workers were involved in this project. At the end of February 2002, 600 of approximately 2000 hybrid girders had already been produced.



Fig. 15: Type I girders on the storage yard

By the end of 2002, the first test trips are scheduled. In January 2003, the first official VIP run will take place, followed by the regular customer's traffic later in the year. This schedule seemed to be utopian, especially compared to German standards. However, the present production is on schedule. And in China a lot is possible, as we have experienced in the meantime.



Fig. 16: Mounting of Hybrid Guideway Girders

## 7 Summary

If this construction progress can be kept, the ambitious objective of starting the Transrapid in 2003 seems to be realizable. The German syndicates will do their utmost to contribute to the success of the Chinese. The success of the Shanghai project will be the basis for further applications of the Transrapid world-wide. We are all looking forward to the year 2003 with great interest and great confidence.

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