Guidance beam manufacturing method for maglev- and high-speed train application

Seppo Hauta-aho
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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall 118, Puumiehenkuja 5A, K3 of the school on 29 May 2019 at 12.00.

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Ordinary embankments have limited applicability as support structures for high-speed trains. Embankments are not used at all for high-speed maglev trains; rather, elevated concrete beams on pillars are used for trains operating with this technology. In rail traffic, the need to develop rapid transport connections has largely focused on the manufacture of high-speed train technologies, more so than tracks. The development of tracks for both maglev and high-speed trains remained an unsolved problem. A reason for this may be that, in the case of traditional ground-supported embankments, higher train speeds and the transport of greater goods volumes have been addressed through train development.

This dissertation addresses how the development of a continuous steel railway beam bridge can help to solve the problems of classic railways and high-speed train railways. In this research, it has been important for the developer and manufacturer of the railway beam to co-operate with the end client in order to create a factual concept addressing the development needs. The research question concerns which kind of steel beam would have the necessary structural strength, and how it could be manufactured within tolerances. The work aims to develop a steel railway beam for maglev and high-speed train applications in order to solve the research question. Due to the technology employed in this research, ordinary methods cannot be used to manufacture a continuous steel-beam railway bridge. This is due to tight tolerances and the necessity of economical manufacture. The product idea and manufacturing method have been developed as an integrated process between the companies in which the end client perspective has been determined by analysing the railway beam structure and the efficient manufacturability of the beams. This dissertation demonstrates that the steel railway beam has been developed as a product structure and manufacturing method system. Many end-user clients benefit from this research. The new manufacturing method developed in this research uses continuous energy input measurement and monitoring during the manufacture of the railway beams specified in the project, and the system stores and reports on the railway beam product and manufacturing data. The manufacturing tolerances of the railway beam are achieved by using the method and its affordable implementation and equipment. The benefit of the new method and system is that the manufacturing process can automated produce a dimensionally accurate railway beam in accordance with the specifications. The aforementioned aspects demonstrate that the system can be used widely in steel construction applications, such as railways, bridges and ships, etc.

**Keywords** steel beam, railway beam, steel beam bridge, continuous, high-speed train, rail beam manufacture, horizontal and vertical curvature, submerged arc welding, energy, invention, patent, steel, train, railway


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PREFACE

Developing guidance beam structure and method for maglev- and high speed rail for applications manufacturing, is an example of solving an international technical problem during very long period.

Scenarios of the three industry evolutions gave important different phases of life cycles of maglev-, steel-beams and classical railways. A new steel-beam structure and new manufacturing method combined with energy input control system developed. This dissertation would not have been possible without the support and assistance of several people.

First of all I want to thank Professor Kari Tammi as the supervisor and supporter.

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Seinäjoki, April, 2019

Seppo Hauta-aho
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<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>HSDA</td>
<td>three-web slant-webbed A casing</td>
</tr>
<tr>
<td>HSDQ</td>
<td>three-web Q casing</td>
</tr>
<tr>
<td>HSDK</td>
<td>three-web K casing</td>
</tr>
<tr>
<td>HSR</td>
<td>high-speed rail</td>
</tr>
<tr>
<td>HST</td>
<td>high-speed train</td>
</tr>
<tr>
<td>Maglev</td>
<td>electromagnetic levitation</td>
</tr>
<tr>
<td>H</td>
<td>total height of the web</td>
</tr>
<tr>
<td>d1</td>
<td>thickness of the edge plate</td>
</tr>
<tr>
<td>d2</td>
<td>thickness of the middle plate</td>
</tr>
<tr>
<td>α</td>
<td>angle between webs</td>
</tr>
<tr>
<td>B1</td>
<td>width of the top flange</td>
</tr>
<tr>
<td>B2</td>
<td>width of the bottom flange</td>
</tr>
<tr>
<td>t1</td>
<td>thickness of the top flange</td>
</tr>
<tr>
<td>t2</td>
<td>thickness of the bottom flange</td>
</tr>
<tr>
<td>L</td>
<td>length of beam</td>
</tr>
<tr>
<td>A</td>
<td>area of cross-section</td>
</tr>
<tr>
<td>g</td>
<td>weight kg/metre</td>
</tr>
<tr>
<td>Iy</td>
<td>moment of inertia in y-y axis</td>
</tr>
<tr>
<td>Iz</td>
<td>moment of inertia in z-z axis</td>
</tr>
<tr>
<td>Wy1</td>
<td>upper surface major axis section modulus</td>
</tr>
<tr>
<td>Wy2</td>
<td>lower surface major axis section modulus</td>
</tr>
</tbody>
</table>
Sy1  static moment of upper flange area
Sy2  static moment of lower flange area
SAW  Submerged arc welding
SAW-T Submerged tandem arc welding
DCEP Direct current electrode positive
NDT  Non-destructive testing
WPS  Welding Procedure Specification
WPAR Welding Procedure Approval Record
x-x  Co-ordinate system of x-x member
y-y  Co-ordinate system of y-y member
z-z  Co-ordinate system of z-z member
WPS  Welding procedure specification
IPR  Intellectual Property Rights
M_{S.d} design value of the bending moment
M_{c.Rd} design moment resistance of the cross-section
W_{pl} plastic section modulus of the cross-section
f_y nominal characteristic value of yield strength
\gamma_{Mo} partial safety factor
M_{el} design moment resistance of the cross-section
W_{el} elastic section modulus of the cross-section
M_{eff} design moment resistance of the cross-section
W_{eff} effective section modulus of the cross-section
D_1 cross-measure D_1 of product type
D_2 cross-measure D_2 of product type
1. INTRODUCTION

1.1 Background and research environment

In 1993, this study started to investigate new technologies to balance the strategic portfolios. For example, production of welded beams on the market was done using inadequate welding, which caused poor quality and high extra costs. According to market analysis (Hauta-aho 1993), these formed a threat to the future of the welded beam business. This statement gave scenarios about changing technology in the world and impact on industries and countries. In the companies Steel-Invest (hereinafter referred to as “Company A) and H-Steel (hereinafter referred to as “Company B) this gave the starting push for the development of technologies. The second push was a declining market in the main markets of industrial buildings, process industrial constructions etc. The key challenge for this period was revitalization, to seek and to see new technology. Scenarios of the three industry evolutions present different phases of life cycles; future - , present and old technology. A comparative study of technologies gave awareness about their strengths, weaknesses, opportunities and threats. The vision of this study was to develop new railway beam types, which can be analysed during the research. The three alternative industries integrated process stages between designer, manufacturer and customer. The goal of this study was to develop new knowledge, which was a focus during the comparative research of missing technology.

Example of future technology - maglev line introduction in 1995:

Planning the Transrapid Berlin-Hamburg led to the “Maglev Planning Company”. The company had a mission to undertake the detailed planning of the first Transrapid line until it was ready for construction (Planungsgesellschaft
The Maglev Planning Company was established in 1994, in Schwerin. The Berlin–Hamburg Super-Speed Maglev Milestones started in 1994 with the Planning Company, after the Magnetic Levitation Service Planning Act, the German Cabinet’s Decision on Construction of Maglev. The construction of the first line sections was due to start in 1999, so the Transrapid could be operational in 2005. The individual steps of option selection to the commencement of construction included: selection of routing options, preparation of documents for regional policy harmonization, decisions for individual line sections, project planning, invitations to tender and the commencement of line section construction. External experts were entrusted with implementing all the direct planning services, compiling expert opinion, and providing analysis and expertise. The Maglev system reaches a maximum speed of 250 km/h in conurbations and up to 450 km/h elsewhere. The plan was to initiate Transrapid operations in 2005.

Examples of present technology - steel beams and manufacturing in 1995:

The manufacturing of steel constructions and steel bridges includes: operation instructions, sales and marketing tasks, purchasing, manufacturing control, inspection, testing and quality control. Work planning designs each work task in detail. The designs are based on drawings from sales, valid standards, norms and other documents for the work in question. Planning and documentation should be completed in such a manner that the manufacturing quality is able to meet the requirements. Completed documents should be sent to the supervisor who is responsible for the work phase in question as well as to the inspection department. Work planning can also involve consulting the designer in order to clarify constructions. Plans are submitted to the manufacturing and inspection departments. An initial meeting for the construction of steel bridges is obligatory and must be arranged if the magnitude or complexity of the work requires it. Representatives from work planning, inspection, manufacture and the sales departments should participate in the meeting. The manufacturing department produces the bridge beams required for the operational stage. The welded plain web girder and profiles are checked to correspond to the requirements of the work instruction and drawings. The beam is moved into
the stud bolt welding point for the concrete deck of the bridge beams. The locations and lengths of the stud bolts are in accordance with the technical drawings. All of a beam’s bolts are inspected for proper welding. When the bridge sections are assembled, the beams are transferred into the test assembly working point. Beams are placed into the correct position in accordance with individual competence tests, which are personally supervised and are in compliance with the applied standard. The same procedure applies for mechanised welding production lines. It is required that welders operating manual submerged arc welding devices have a manual welding certificate. Butt web welding is used in submerged arc welding.

Examples of old technology: classical railways in 1995:

The planning of classical railways considers sleepers, embankments, geometry, tracks and ballast constructed on site. Classical railways mostly do not have bridges, but are constructed on land. The ballast bed rests on the sub-ballasted layer, which forms the track supporting structure. Since the birth of railway in the 1830s, train speeds have increased from 30 km/h (Gourvish, 2012). However, the principle of the ballasted track structure has not changed. The increase in the speed of trains has been one of the most innovative forms of passenger transport since the Second World War. At the same time, classical railway embankments have become increasingly more expensive to construct. This is due to old technology being utilised in the transport infrastructure. Pre-war speeds were increased by deploying improved locomotive technologies on the existing infrastructure. Also, classical railways with embankments are demanding to accommodate urban areas. Bridges, elevated railways, and other flyover passages make planning easier in, for example, planning cities.

1.2 Research questions and the need for a new approach

This research stems from a lack of information about the potential of steel-beams for steel-beam guidance for high speed railways.
Key questions concern what kind of new steel-beam structures are needed and how they can be manufactured economically to tight tolerances.

To answer these questions, this research started by looking at the technological requirements for the Berlin-Hamburg railway (FWG Magnetschnellbahn Fahrweggesellschaft mbH, 1998a, 1998b, 1998c, 1998d). It was important to understand the need for new steel-beam and manufacturing technology. There was the question of the Transrapid guiding design. The guidance beam could not be manufactured in accordance with the necessary technical requirements.

In this dissertation, the author identifies the technological barriers to manufacturing the guidance manually, including the fact that capacity could not be calculated reliably. The author has information concerning production capacity requirements and drawings. These are based on the “Berlin-Hamburg Super-Speed Maglev Milestones as of June 1997”, and for the timed construction of the guideway planned for 1999-2003. The time calculations were impossible to reach within the deadline, as the period was unrealistic. The lack of time was a driver and starting point in the search for solutions. There was a gap between the designed construction of Transrapid steel-beam and their manufacturing methods. Further to this, traditional technology builds ground-supported tracks lying on embankments. This kind of ballasted track and slab track is used in France, Germany, Italy and Spain. Regular maintenance is required to repeatedly restore the track alignment. Due to deficiencies, there is a clear need for a new steel-based foundation solution for steel-beam guidance.

1.3 Research problem and research stages

The long-term research on the new steel-beam and new manufacturing methods started in this study. In the strategy, environment the focus was on the evaluation of a new industrial environment and entry opportunities (Hauta-aho 1993).
One problem is maglev guidance construction, its design simplifications for manufacturability. The guidance does not keep to the tolerances after manufacturing, due to deformations caused by heat input directed to the seams of the maglev guidance structure during the production process. For example only one of the five guidance remain after manufacturing in tolerances (Flessas 2002); (see tolerances reached in this work in Table 5 and Table 13).

The second problem is steel-beam manufacturing and fabrication capability for large steel structures in tolerances. A finished beam that is not in accordance with the tolerances cannot be straightened or made to comply with the specification afterward. The problem could include the influence of various process parameters, beam distortion, and the required tight tolerances (EN 1993-1-1 Eurocode 3).

The third problem of a classical railway is foundation technology for a high-speed or higher-speed system. There are factors that highlight the difficulties in comparison. These include the frost hazard, soft soils, purpose of the railway, and design parameters, but also other aspects that are difficult to identify.

In the beginning of the research, the problem was in obtaining a better understanding of maglev guidance, the steel-beam structure and manufacturing method, and their connection with classical railways. At the same time, various solutions were analysed (Fig 2). In order to address the previously mentioned problems, a solution was reached as described in Fig. 1.

Previous studies were used as a framework when planning a new field, stage by stage. However, it was not known how long it would take to find ideas to solve the current steel-beam problems. The framework for the identification of global markets and technology information was identified. However, individual technologies were not considered in depth, but as a direction for research. Information led to the understanding of technology problems, but not the specific details. This led to the definition of the substantial technological problem in railways found in the market itself.

By following the above stages in the maglev industry environment, the author was able to develop an understanding of the topic, identifying new directions in international markets and the technological problems within them. Maglev information led to the analysis of train guidance technology; a rough design for steel-beams that fulfils the specification and can be manufactured cost-effectively.
1. Vision of the idea:
Long-term research on the evaluation of entering a new sector

2. Consideration of requirements of steel beams and manufacturing methods

3. Designing new structure strengths:
   Choice of manufacturing tools

4. Choice of structure for new beams:
   Testing strength parameters

5. Recognising new manufacturing methods:
   Testing existing manufacturing

6. Repetition of tests:
   Beams' strength tests, manufacturing tests

7. Acceptance of patents

Fig. 1. Research stages in this work

A comparison was made between different steel beams and between manufacturing equipment. Various parts and components, the substitution of existing steel plates, and the strength of materials were analysed. The comparison included the analysis of current welding parameters, tested steel plate distortion and the welding process when joining steel plates together.

Over time, the knowledge gained was built up from the initial idea through development. The development in this work was a systematic process requiring input from a wide variety of sources. Scientific and technological developments, competitors, engineering suppliers and manufacturing markets were important (See Rainey, 2005; Trott, 2008).
A literature study is presented in detail in Chapter 2. Chapter 3 describes how the existing materials cover only part of the problem of what kind of new steel-beam structures are needed, as well as how they can be manufactured economically within tight tolerances.

The manufacturing method and steel-beam structure testing are presented in Chapter 4. There are estimated calculations for cost differences between the steel-beam guideway and classical embankment rails. Testing of steel-beam welding parameters for the guidance of jig beams included distortion measurements for each one. Tests of I- and box-beam profile strengths contained the strength of the steel-beam by unit of bending. The energy input measurements included two jig beams and the structures of two beams. An energy input control system used for jig beams is presented. The strength calculations of three scaled steel-beam types are calculated for other types and sizes of each steel guidance beam.

In Chapter 5, the results are discussed in the light of a new state of the art energy input control system, evaluation of the research, answering the research questions, recommended dimensions for applications and further research presented in this chapter. The conclusions of this research and contributions are presented in Chapter 6.

1.4 Scope of the research

A steel-beam is a horizontal or inclined support used in construction engineering. The task of a steel beam in a structure is to support upper structures, such as floor slabs, a roof, ceiling, bulkhead, bridge, road, or rails.

In many applications, the beam is to be used has a precise specification, definition, and instructions according to which the beam is manufactured. This incurs a problem that a steel beam does not maintain the same tight tolerances after manufacturing. Deformations are caused by heat input directed to the seams during manufacturing. According to the conventional welding procedure specification (WPS), measurement of heat input is made once per order, or per project. Measurements are not observed on the process level for an individual product. The existing welding procedure measurement is insufficient to obtain the objectives of energy input control for manufacturing steel-beam guidance.
The existing measurement does not monitor the straight beam, the vertical up/down and horizontal left/right tight tolerances during the manufacturing process. A finished steel-beam structure does correspond to the tolerances, it cannot be straightened or made to comply with the specification afterwards.

Thus, the goal of this dissertation is to develop a steel beam, a method for manufacturing the steel beam, and equipment implementing the method. These developments would solve the measurement problems in the conventional welding procedure. The data presented in this dissertation are based on real steel-beam production and pilot machine data.

1.5 Scientific contribution

Advantages are provided by the method and system. It is possible to manufacture automated a final product complying with the manufacturing tight tolerances. The method, equipment, and steel beam as well as their utilisation can be applied to many different purposes. Not only for maglev guidance beams (See Hauta-aho, 2011, 2013, 2014, 2016a, 2016b, 2016c, 2016d, 2016e, 2017a, 2017b, 2017c). Steel beam structures can also be used for high-speed rails (HSR), railway bridges, steel-bridges and cargo wagon beams. These applications are new to the scientific community.

Furthermore, taking into account the steel beam and the preferred way in which it is applied, the manufacturing method and equipment also take monitoring and/or measuring factors into consideration. This affects one or more deformations of a steel-beam part, steel beam or steel-beam entity, and takes any necessary action. Adjustments of the various factors affecting deformation can be corrected automated or with a combination of automated and manual actions. If possible, the product is heated manually in manual straightening. This method and equipment utilise control equipment for manufacturing a steel beam which performs the actual energy input measurement. Thus, the equipment comprises an automated deformation measuring system. The novel control system of the equipment monitors the energy input to the product’s welds by each weld or weld group. The equipment controls the energy input in the process through each weld or weld group. The
system minimises deformation in the product being manufactured and reduces the need for straightening. In addition, the manufacture of the product is less expensive on a factory scale.

Thus, the beam and its implementation methods are not restricted to the examples described above, but may vary in scope. The development presented in this dissertation has resulted in the following research contributions which are new to the scientific community:

1. The study presents novel steel-beam structures which are competitive with classical foundations.

2. The study presents a novel manufacturing method for a large steel beam when the steel beam is challenging and the achievable tight tolerances depend significantly on the design of the steel-beam structure.

3. The study presents analyses of I- and box-beam strength and weakness tests, while creating a novel steel-beam structure.

4. The study impacts on a novel energy measurement system in the guidance manufacturing method.

The system can be applied for manufacturing maglev-, high-speed rail guidance, steel bridges, railway steel-beam bridges, and similar large steel structures. The beam design, assembly procedure, and the way to use welding energy input data during manufacturing, offer a new overall design procedure for engineering sciences. The design also considers techno-economical aspects in order to design and manufacture viable products. Without excessive risk of manufacturing products which do not yield the tolerances required.

The dissertation also contributes to practical work shop processes and sustainable design and manufacturing. Several tonnes of steel waste can be avoided, as the manufacturing of large steel structures has made the results more reliable.

Relative to the existing scientific publications, this dissertation presents, for the first time, a steel-beam bridge foundation where the comparative guidance solution does not exist in the classical railway foundation. The steel-beam solution may also become useful for other fabrication industries in the future.
The manufacturing technology and related steel-beam structure parameters and cost components can be calculated in order to search for the best achievable guidance steel-beam strengths. In addition, most of the parameters are new to the scientific community.

For a decision maker, it is important to understand the effect of new technology on cost saving and profit achieved. The comparison between the current railway foundation on site and current profile manufacturing lines does not provide the decision maker with the best achievable cost-saving possibilities. The reason is that new technology and optimal new technology cost-saving parameters are not taken into account.

These technologies are new to the scientific community. Parameter values exist which can be optimised to produce the greatest cost-saving potentials. Based on these, the optimal of steel-beam structure and manufacturing method together with sensitivity and risk calculations achieve cost-saving potential.
2. EXISTING METHODS FOR ENERGY INPUT CONTROL IN WELDING

This chapter briefly presents the basis of the methods used for manufacturing materials to tolerance requirements.

Kazanowski & Misiolek (2002) presented an evaluation of residual stresses and their influence on distortion in the de-coiling and welding processes from the perspective of steel. In construction, the researchers applied the physical model presented by Ashby (1999), Kazanowski & Misiolek (2002). According to Ashby (1999) the first stage consists of the identification of the problem and a consideration of the likely physical mechanisms involved. A model should be constructed using the most advanced theory available after making a thorough assessment of the published literature. This identifies areas where adequate knowledge does not exist.

Following research, the goal was to develop a model, which can describe the influence of different processing parameters and material characteristics on plate distortion. Considering the maglev guidance material, it is not necessary to only analyse and understand the plate’s spring back during uncoiling. Also, the origin of the residual stresses responsible for plate distortion was investigated. The distribution of residual stresses in the uncoiled plate is not uniform and needs to be understood and quantitatively described. The plates are coiled immediately after hot rolling. Consequently, the plates are either free from residual stresses or their level is very low. The plate material after de-coiling is not ready for further processing such as welding. It is necessary to straighten and flatten the plate, which after de-coiling in room temperature has built-in residual stresses. The steel guideway beam is fully welded with integrated functional components, lateral guidance rails and gliding plane. The main objective of the mathematical model was to find the relationship describing the evaluation of residual stresses and the influence on distortion in the de-coiling and welding processes. The problem definition was based on the
Transrapid guideway, which is an integral component of the Transrapid Maglev System. A guideway consists of high-precision welded steel or reinforced concrete columns and foundations. The overall system ride is directly related to the execution and quality of the guideway. Therefore, guideway specifications and tolerances relate to riding comfort and as such are especially important. Researchers found it very difficult to describe and calculate stresses in each part of a coil during the de-coiling operation. Numerical simulation of the bending of a curved plate was performed. The initial geometry for the numerical simulation of plate bending assumed that the upper plate moves vertically at a speed of 2.5 mm/s. The lower plate was in the same position for the whole simulation. For each radius, three different plate thicknesses were used: 3.175, 6.35 and 9.525 mm. After the tests, the researchers came to the conclusion that the distortion during welding is dependent on the de-coiling history. The researchers used technological guidelines to maximise the productivity of assembling large steel structures by welding. Thus, de-coiled plates with special focus on the guideway assembly for maglev trains was established. The researchers did not analyse the welding processes they used. The same applies to the de-coiling material thicknesses based on the Transrapid guideway. The research passed welding processes in evaluation of residual stresses and their influence on distortion in the de-coiling.

One reason could be incomplete knowledge concerning the influence of heat on welding. For example, Singh et al., (2015) found optimisation of parameters for polarity in submerged arc welding. Furnishing the quality welds requires both direct current electrode positive (DCEP) polarity and direct current electrode negative (DCEN) polarity. Optimisation of welding parameters is essential to achieve high quality and cost-effective welds. The researchers used a submerged arc welder machine (tractor type). A machine runs on the base material to obtain the working parameters. Experiments were performed in a random manner as per a design matrix to avoid any systematic error. Specimen plates were prepared by making beads on mild steel plates with the dimension of 300 x 100 x 12 mm, using the EL-8 electrode of 3.2 mm in diameter and flux Ok 10.71. The researchers found that polarity change had a profound effect on the weld bead geometry in submerged arc welding. DCEP polarity welding was smoother compared to welding, which was observed during the welding process. DCEP polarity exhibited higher volume value of weld bead response
parameters except reinforcement. Also, mathematical models were developed for various response parameters for DCEP and DCEN polarities. A tractor moved on the plate during measurement.

According to Quintino et al. (2013) the researchers’ methodology was based on a comparison of the heat absorbed by plates of two different thicknesses (one to achieve full penetration and the other for partial penetration), obtained by cryogenic calorimeter. The measured heat quantities and the calculated welding energy (using the instantaneous power method) were used to calculate the welding efficiency. The welding conditions remained the same for all runs. In MIG/MAC welding, a 1.2 mm wire was used with a travel speed of 34 cm/min. The contact tip-to-work distance was 12 mm and the feed speed was 3.6 m/min. The bead on the plate welds was performed over two carbon steel plates (AISI 1020 grade) with a thickness of 3.2 mm and 9.5 mm, both of which are considered to be thin plates for these welding parameters. The welding procedure was optimised to ensure full penetration welds in the thinner material. For comparison purposes, various bead lengths (from approximately 10 to 150 mm long) for each thickness were deposited. The welding time lasted from 3.21 to 28.8 seconds. The absorbed heat was measured as a function of bead length, for fully penetrated welds and partially penetrated welds. One result was that heat input to the plate is null if there is no weld bead. When the length of bead was 160 mm, the total absorbed heat due to welding (kJ) was 70–80%. A methodology for comparison of heat input for partially fully penetrated welds was presented, using cryogenic calorimetry and thermography. The welding efficiency factor needs to be adjusted when applied to root passes or full penetration welds. This will bring cooling rates and respective metallurgical transformation and mechanical proprieties predictions closer to reality. The length of the welds and even the holding time influence the heat input. In calorimeter studies, it is advisable to use the same conditions to compare results.

Kiran et al. (2014) investigated the two-wire submerged arc welding process (SAW-T) in a high-deposition welding process. SAW-T is capable of improving productivity while welding plates with medium to high thickness. In this welding method the leading wire was connected to either DC or AC and the trailing wire to AC. The ease of use for the SAW-T process is less when compared to the single-wire SAW process. The welding used 780 mm x 360
mm x 17.5 mm plates to perform bead-on-groove experiments. The groove angle was 60° with a depth of 8.5 mm in the SAW-T process. The researchers presented the variation of arc centre displacement and arc root dimensions with the welding condition. The two-wire tandem submerged arc welding process, where there are trailing arc (trailing wire) centre displacements, was more sensitive than the leading arc (leading wire) at the same welding current. For a constant leading arc current, a decrease in the trailing arc current makes the latter more unstable. Also, significant influence by the arc interaction on the arc root dimensions was evident. The effective length of the leading arc front was greater than the rear. In the repulsion mode while trailing the arc front, it was smaller than the corresponding value of the rear. Significant influence by the arc interaction on the molten droplet transfer direction was found. Significant influence by the arc interaction on the molten droplet transfer direction was evident. The molten droplets from the leading and trailing electrodes followed the axis of the corresponding arcs at the time of detachment and reached the weld pool. Research shows the instantaneous current and voltage waveform of the leading and trailing arcs and their effect on arc interaction. It refers to the leading arc-based current and magnetic field, generated by a trailing arc value of 1000A each with voltage values of 32 and 35V. The research shows the influence of welding conditions on the arc interaction: the welding current waveform, voltage waveform, arc interaction and arc images. The research did not show calculations of energy input by using SAW-T welding. The study used the V-groove welding, and the molten droplet was not clearly visible. A difficulty of SAW-T welding is double energy input together with the lead arc and trail arc. Heat input causes a distortion effect which was not evident in the plates used.

Mesquita da Silva et al. (2017) evaluated the influence of welding variables on weld beads. Researchers used the submerged arc process with conventional current, with the aim of future application in overlays against corrosion. Welding is one of the main fabrication processes used in various segments of metal-working, such as in mechanical engineering industries related to shipbuilding and boiler-making services. The process was used quite widely in the fabrication of onshore and offshore platforms, oil tankers, storage tanks, pressure vessels, chemical reactors, and oil/gas pipelines, etc. For corrosion-resistant coating, it is essential to reduce the Fe content on their surface and
avoid the formation of microstructures susceptible to corrosion. For this, it is possible to use techniques or procedures to reduce the welding energy in order to ensure less distortion and penetration. The techniques include changing the type of current, inverting the polarity of the current, or changing the CTWD (Contact Tip Work Design). In addition to the multiple arc techniques, there is also hot wire and strip overlay welding. The researchers found that it was not possible to adjust the current on the machine to the desired values while welding with conventional current. Moreover, it was not possible to use it as an input variable in the factorial design. All the beads had minimum heights greater than 3.4 mm.

Wu et al. (2017) investigated metal transfer in submerged arc welding. Based on high-speed videography technology, the behaviour of metal transfer in SAW was filmed through a stainless steel pipe. The information about welding electric signals was obtained by Analysator Hannover. A physical modelling experiment was carried out to simulate the metal transfer in SAW. The results suggest three different metal transfer modes in the SAW process. At lower current, repelled globular transfer without short-circuit would occur. At medium current, since the droplet may be repelled to the surrounding flux wall, flux-wall guided transfer without short-circuit would occur. At higher current, the droplet may flow into the molten pool along a continuous stream attached to the flux wall; thus flux-wall guided transfer with short-circuit would occur. Further analysis indicates the electric arc and short-circuiting bridge may exist simultaneously when the third mode occurs, which is a completely different form of GMAW (Gas Metal Arc Welding). In testing, SAW welding the researchers used Q235 mild steel with dimension of 250 mm x 120 mm x 15 mm. The welding wire was a diameter of 3.2 mm and the flux was their nominal chemical composition. In this groove test, the work piece was in place and the welder was moving on a small plate. Perhaps because of the small plate, the researchers could not adjust the travel speed at all, forgetting to calculate the importance of energy input for metal transfer in SAW.

Jorge et al. (2017) analysed active power measurement in arc welding and its role in heat transfer to the plate. They support the importance of energy input produced by electric arc and transferred onto/into a plate. Heat input is extremely important. Not only for bead geometric formation, but also for metallurgical transformations. It influences the mechanical properties of the
joints. Heat input is proportional to the arc energy, which in turn is a ratio of arc power and arc travel speed. In experimental procedure, researchers used in stage 1, a constant x pulsed current in the GTAW (gas tungsten arc welding with thermocouples embedded in horizontal flat plates) process using a test plate of 198 x 38 x 9.5 mm bead-on-plate in welding, using wire diameters of 4 mm. In stage 2, a constant x pulsed current in GTAW supported by calorimetry using test plates of 200 x 100 x 6.3 mm and the electrode-plate distance was 3.5 mm. Stage 3 was the variation of active power through inductance setting in GMAW. The plate size was 150 x 38 x 6 mm, varying settings in the power source, whilst the other important parameters were retained. They found the gross powers of the three experiments increased slightly from the lowest inductance to the highest one. The research found large signal variation in voltage and current values in the GTAW process. The researchers recognised that modelling the arc as an equivalent electrical circuit was not an easy task. In this research, the plates were in place and the weldment moved on those.

**Summary of Chapter 2**

The literature shows that there is a need for a steel-beam manufacturing method. The maglev guideway is one example of steel beam, beam length, size, speed, etc. Steel is becoming one of the cost-effective materials. This comes as a result of the development of steel material handling. The literature showed use of coils but emphasised the resulting problems from de-coiling. Also, the distortion results were presented without attention to the welding processes involved.

The welding process used in the literature was by welder types, where the welder moved on the V- groove plate (plate preparation to V- form before welding). Investigations were made by using GTAW, GMAW, SAW and SAW-T welding methods. All weld tests were made on small plates with variations of current (A) and voltage (V). For example, SAW-T welding means double the energy input to welds, but this was not calculated.

The elimination of distortion requires a new suitable manufacturing method.
3. MATERIALS AND METHODS

During the last 20 years, there have been numerous projects to analyse individual workflows (See Hauta-aho 1992, 1993, 1994, 2003). The workflow at factories A and B included welded structural shapes for bridges, cranes, buildings, shipbuilding, railways, power stations and other undertakings.

Based on the studies (Hauta-aho 1993), a comparatively small space (25 m x 50 m) and low capital investment are required to set up a welded beam production line. The process represents an ideal method of steel-beam production compared to rolling mill-based standard beam production. The production capacity depends on the size and configuration of the steel beam produced. This is the keynote of its design. In practice, the plates are placed onto the input side of the machine where they are automated correctly positioned in relation to each other. Steel beams can have flanges and web of different materials; also, these flanges and webs are of varying widths and thicknesses. This kind of mechanical capacity is not available in rolling mills and manual manufacturing.

The empirical analysis of welded beam production technology created an ideal solution for producing steel beams for Transrapid guidance. This led to making observations for many projects in order to examine workflows based on steel beams and welding lines from a new perspective as a steel beam. The technology for the steel-beam guideway and manufacturing forms the basis for the new workflow. The questions concerning what will be measured as well as how this will be carried out are presented in Fig. 2.
Fig. 2. Method and beam structure development process leading to an alternative welding line system, where the beam is moving.

3.1 Planning of railway foundation

3.1.1 Generating the idea

The planning process comprised a company aiming to commence activities in a new branch (Hauta-aho, 1993). In this work, the idea was generated by identifying technologies from a future, present and old perspective (see Fig.1). Therefore, it was necessary to understand information from global fields, customers and suppliers in relation to the idea. Strategy in this work was based
on the vision of the future of steel beams. Generating the idea focused on gaining an understanding of the environment of the railway foundation.

Rainey (2008) examined new product opportunities involving the generation, development and evaluation of ideas for new products. The fundamental steps included understanding the needs for new products. However, it was also necessary to discover existing and potential sources of ideas. As a result, internal and external requirements were described, and opportunities assessed. Idea generation represents the genesis of the new product development process. The most obvious source of ideas is a company’s own R&D (Trott, 2008). This is also the view of product developers and manufacturers (see also Saren & Tzokas, 1994).

Classical railways planning has to consider the soil type and train speed. Currently there are many planning parameters, such as radius of curvature $R$ [m], rail tilt $D$ [m], rail tilt shortfall $I$ [mm], excess $E$ [mm]. Changes of tilt per unit of time $dD/dt$ [mm/s] and changes of tilt per unit of length $dD/ds$ [mm/m]. Also considered are parameters of changes of tilt shortfall per unit of time $dI/dt$ [mm/s] and uncompensated cross acceleration on track level $aq$ [m/s²]. As well as the consideration of uncompensated change of cross acceleration $daq/dt$ [m/s³], length of planning parameters (radius, straight) $Li$ [m]. Moreover, the length of easement curve $LK$ [m], bevelling of tilt $LD$ [m], vertical curve $RV$ [m], vertical acceleration $av$ [m/s²], and speed $V$ [km/h] (See RIL 179, 1989; Finnish Rail Administration, 2010a; Jin et al., 2016) also need to be taken into account. All these factors are required for the planning of one set of rail geometry.

Further to this, Lamas-Lopez et al. (2016), investigated axle loads and train speeds. These play a significant role in the selection of track-bed materials. Cyclic strains and various soil-confining pressures were considered for cycle tests from 25 kPa to 200 kPa. The test results showed a decrease in the resilient modulus of the soil, similar to when the strain amplitude is increased. Decrease of the resilient modulus could involve an increase of the material plastic deformation when the train speed is upgraded or the axle load is increased on the line.

According to Lindahl (2001), the horizontal curve radius is a function of allowed cant, cant deficiency, and speed. The curve radius must be sufficiently large to cope with the desired speed for both conventional and tilting trains respectively. For example, if a conventional high-speed train is to be run at 280 km/h and
tilting trains at 350 km/h, the horizontal curve radius should be at least in the order of 3200 m. With respect to heavy freight trains, speeds of above 250 km/h are not allowed on high-speed lines.

Kilinc & Baybura (2012) present the criterion of lateral jerk, lateral acceleration, and super elevation. These give a minimum horizontal curve radius from 20 to 250 km/h for railways. Lateral jerk was 0.3-0.9 m/s³, lateral acceleration 0.65 m/s², and super elevation 4%.

Von Braun (2011) developed a planning methodology for railway construction cost estimation in North America. Planning includes the possibility to calculate cost per mile (CPM) accounting right-of-way (ROW), design and build materials, communications and signalling, and electrification, where applicable. The methodology is for estimating CPM of railroad construction in the U.S. Parameters are as follows: a function of design speed, geography, land use, number of tracks, and motive power. The result showed, after sensitivity analysis, a better representation of CPM cost by taking potential variability in the cost components of the methodology into account. The results showed the contribution of each cost component to the total cost. It could be observed that the design and build category had the greatest influence on the total cost. For example, with train speeds of 110 mph (177 km/h), an upgrade to single non-electric track with suburban hills contributed 71% of the total cost. Where the speed was 150 mph (241 km/h) and double electric track on suburban plains was constructed, the design and build category was 65% of total cost.

Johnson (2016) includes layout sheets and project bid item summaries. Those were for bridges, culverts, retaining walls, sound walls, sign support structures and miscellaneous structure projects. The book includes typical bridge bid item prices, wall unit prices, and sign unit prices. Bid item costs for the last three years and weighted average unit costs were also included. However, the deck area and its cost were excluded for the following project. These findings are from research where there was only one steel girder bridge with a length of 175´ (53 m). Moreover, it was a single span bridge at a relatively low cost of 136.62 USD per square foot (1,470 USD/m²). The other was concrete bridges with highest of USD 370.85 per square foot (3,991 USD/m²).
Traditional technology involves building where the ground-supported tracks lie on top of embankments. This kind of construction is widely used in HSR in France, Germany, Italy and Spain, but the train speed is slower than with maglev trains. The cost data for the above countries has been published, e.g. in Gourvish (2012).

Iwnicki and Bevan (2012) presented the significant cost to all railway vehicle operators and infrastructure owners caused by damaged wheels and rails. In addition to the actual effort involved in turning, tamping, grinding and replacing wheels and rails. The impact of the downtime on the operation of the railway system is a major factor in reducing reliability, availability and efficiency. Rolling contact fatigue was not a new phenomenon but has become a more significant problem in recent years. Problems partly arise from increases in performance with higher axle loads, speeds, and traffic. Problems are also partly a consequence of improvements in the wear resistance of steels used in wheels and rails. Relatively sophisticated techniques have been developed in the UK and Sweden.

Varandas et al. (2014) investigated track stiffness, which may vary rapidly, and often differential settlements take place between the stiff structure and section of the track. These differential settlements lead to uneven track profiles. It may also lead to the appearance of voids between the base of the sleepers and the ballast on the approach segment. The ballast and the sub-ballast are the unbound granular materials which carry the track. They have a non-linear stress dependent behaviour and degrade many times faster at transitions. The study focuses on the implementation of these non-linear aspects in a finite element algorithm for the dynamic simulation of a railway transition.

Grubb et al. (1998) presented some basic ideas and concepts which may help lead to an improved foundation for steel bridge design. Soil conditions often direct the use of pile-supported foundations where the objective is to minimise the number of piles. The total number of piles cannot be less than the number required to resist full-factored vertical load. Lateral loads create an increased downward force on some poles, but not an increase in the total vertical force. Researchers suggest that more piles are installed than are necessary to resist the vertical loads. It can be hypothesised that an improved substructure design may be possible. This should be considered when attempting to minimise the number
of piles. It is advisable that, where possible, the vertical loads from the superstructure are transferred to the ground through a single shaft.

Existing classical railway technology is evaluated roughly from the point of view of steel beams and the manufacturing of those beams. Technological change plays an important role in the planning of the future railway industry. Referring to steel-beam track foundation, the new technological solution lowers cost and uniqueness drivers in favour of firms and entry into the new industry. An important foundation is that researchers are searching for solutions to classical railway problems.

3.1.2 Recognising classical foundation technology

Many classical foundation problems were discovered after World War II. Esveld (2001, 2017) presented factors such as lack of space, congestion, lack of safety, emission of harmful substances, and noise pollution. In these cases, railways can have advantages. It should be noted that the track must be constructed in accordance with the trains running on it, in order to avoid excessive environmental pollution in the form of noise and ground vibrations. The cost of the total service life of the track must be as low as possible. Also, maintenance should be as low and inexpensive as possible. Classical track structure includes axle load 225 kN max and rails 900 N/mm². Moreover, there are fastening systems, sleepers, concrete or wood with a spacing of 0.6 m, 25-30 cm ballast (crushed stone), 10 cm gravel and subgrade.

Amblard et al. (2015) note conditions when water and debris flow from the platform, which may drag the ballast off the track foundation. The rate of ballast erosion rises when obstacles are placed along the platform.

Also, Lopez-Caballero et al. (2016) present evaluation of the dynamic behaviour of railway soil foundations using in situ buried instrumentation. Research shows the response of the rail-embankment-ground system is mainly non-linear elastic.

In Sweden, Lindahl (2001) found most companies classify their tracks with regard to the level of permissible track irregularities. Generally, fewer irregularities are permitted on high-speed lines. Lines for lower speeds refer to the classification in the CEN/TC 256 WG 10 as well as Banverket BVF 587.02.
Lindahl suggested the optimisation of track geometry with respect to the required train performance. The cost calculations for removing different topographical or other obstacles should be made. Optimisation studies should be made for each individual section of any proposed high-speed line.

Momoya et al. (2016) presented three different solutions to properly maintain degraded ballasted track. One is roadbed improvement. The second is the improvement of the degraded ballast by polymer aqueous solution. The third is stabilisation of the ballast layer by fine particle cement grout.

In Finland, the economic advantages of railway track construction projects are analysed. Cost-benefit analysis is one accounting method for life-cycle costs. There have been some problems in collecting profitability calculations and studying life-cycle costing in railway track construction, the research of which has been based on literature and interviews. The observations showed major developments are required in the method of profitability calculation. Furthermore, the openness of the results and decisions could be improved (Finnish Transport Agency, 2011; Uusi-Rauva, 1989).

Silla (2013) suggested building physical barriers to improve the safety of classical railways by preventing trespassing problems (see also Wahlgren, 1975; Gourvish, 2002; Braccilli, 2012; Chen et al., 2012).

Lindahl (2001) analysed the vehicle dynamics of track irregularities in the longitudinal direction of trains. Four irregularities were described: vertical, lateral, cant and gauge irregularity. The so-called Q-value of the reference irregularities was calculated. The Q-value is a measure of the average standard deviations with respect to the comfort limits of Banverket’s standard classification. The study referred to Banverket’s quality class K0, which is the quality class defined for speeds in the range of 200km/h. It is above 145 km/h for conventional trains and above 185 km/h for tilting high-speed trains. The various combinations of track irregularities and characteristics were presented per track (see also Woodward et al., 2015).

Also in Finland, individual cross-sections of embankments have been designed to consider protection against the effects of freezing, soft soils and the moisture content of soils. Cross-sections are designed for lower speed, and in some land areas, for higher speed trains. There is a clear need for steel-beam bridges. The
current target of developing and modernising rail traffic is higher train speeds. (see Finnish Transport Agency, 2014a, 2014b; Vican et al., 2016).

The planning parameters of classical railways are standardised for the stability and moisture content of soil types. Some investigations have been made concerning classical railway foundation technology (see Rantala et al., 2013, Kerokoski et al., 2013).

In classical railway literature, sleepers are the main construction component when considering railway functionality. (Rantala et al., 2013; Esveld, 2001; Zand & Moraal, 1997; Queiroz, 2006).

Instructions are available to calculate the maximum load capacity of sleepers (see Queiroz, 2006; Rantala et al., 2013; Routil et al., 2016).

Classical railway problems can lead to feeling uncomfortable as the speed of the train increases. More discomfort occurs when there is a need to increase the axle loads of a train. As a result of this, in several locations in Finland control has been introduced on how well railways carry the loads as defined in the EN standards for railways classed in the TSI-Infra without reinforcements. The results show Finnish railways cannot carry loads according to the EN standards (Finnish Transport Agency, 2012; Esveld, 2008.)

Research by Indraratna et al. (2012) points to the stabilisation of soft soil foundation problems. Using pre-fabricated vertical drains can improve the overall stability of track and reduce the differential settlement during track operation. A special paper presents the results of laboratory testing, full-scale field monitoring, theoretical modelling and finite element analyses. It demonstrates the beneficial use of geo-synthetic grids, shock mats and drains for rail infrastructure.

In Finland, high speed train tracks also need to consider Finnish soil layers, which often consist of marshes and land which have risen from the sea bed as a result of rising land. Due to the soil conditions, railroads cross and follow clay and peat areas in many places. Large parts of the railroad network have been built on embankments of soft soil. Geotechnical stability needs to be established for categorization. For some railroad lines, detailed information on existing geotechnical stability is based on existing guidelines. The geotechnical stability of all 6,000 km of Finnish Railroad lines cannot be calculated using traditional
methods. (See Finnish Rail Administration 2010b; Andersson-Berlin et al., 2011).

Petrenko et al. (2013) found the same problem. The researchers determined the parameter of shear resistance, determining the development of deep deformation in foundation soils. The analysis showed the need for accurate analysis of ground mass work. It is necessary to develop a generalized methodology for analysing the interaction between the rolling stock/railway and subgrade. Not only should the state of soil subgrade stress be analysed, but it should also take its deformation into account.

Gourvish (2012) studied 45 HSR projects (track on sleepers on embankments). The research revealed the costs of the HSR construction. Without design costs, the land acquisition and equipment costs ranged from EUR 6 million to EUR 45 million per kilometre. When land acquisition costs are taken into account, the cost range per kilometre is most likely very wide. Land is sometimes very expensive and the land acquisition process is time-consuming.

Ollivier et al. (2014) analysed variable amounts of high-speed rail construction in China. The researchers calculated the percentages of all Chinese high-speed rail projects supported by the World Bank. The civil work category included embankments, bridges/viaducts with World Bank support for 48% (speed 350km/h), tunnels 50–54% (speed 250 km/h) and tunnels 44–51% (speed 200 km/h).

Studies have also criticised the speed of trains. For example, in California the imputed velocity of the CHSRA (California High Speed Rail Authority) trains used in designing the network have travelled as fast as 354 km/h (Vranich et al., 2013). The researchers point this out in comparison with the world's fastest train, the French TGV. The latter reaches a speed of 320 km/h.

The CHSRA's speed is too high. (see Esveld 2001: safety limit according to the SNCF, high-speed operation, < 350 km/h is the absolute safety limit). The TGV trains run on ground-supported tracks lying on top of embankments. However, CHSRA train speed may be higher than the TGV trains if the tracks are built utilising modern technology.

Calculations are based on foundation engineering and ground plans. Many kinds of layouts exist for various beds as well as for lowering ground water, bottom overhand benching or. in general, major soil explorations, etc. (Finnish
Rail Administration, 2002). Literature concerning strength calculations for classical rails over embankments shows too many variables to manage when the train speed is high (HST). These are the main problems this work aims to solve (Fig. 3).

![Image showing a railway track in a soft soil environment.](image_url)

**Fig. 3.** Example of the soft soil under classical railways in Finland. Large parts of the existing railroad network have been built on embankments which are on soft soil.

The railways have an allowed axle load of 22.5 tonnes or 25 tonnes, and the line load for both is 8t/m. There is old axle geometry in Finland and EN 15528 axle geometry. The old Finnish classification and new European classification cannot be compared, and the true load-carrying capability is unknown. The parameterised model was presented in Symposium Georail 2011 (Andersson-Berlin et al., 2011). The model included 65 parameters: 11 informational parameters, 28 geometrical parameters, and 26 soil parameters. A laser scanning method was used to measure the thickness of the railroad embankment in peat areas, as well as when determining areas of soft soil. This method was used in order to measure embankment height in relation to the surrounding soil level. In this way, about 3,000 parameterised cross-sections covered 6,000 km of railroads.
The new beam discloses the technology by which ground-supported tracks make it possible to reach and exceed the existing high speeds (see also Hölster, 2012, when a high speed line is built on soft soil). The problems of classical railways are as follows: 1) the maximum speed of trains, 2) strength of soils, especially soft soils, and 3) costs of embankment structures at higher speeds (see Koskela, 2011).

The research showed there are hundreds of rails in Finland which have less capacity for trains and do not fulfil TEN-T (Trans-European Transport Network) network requirements. One special matter which affects calculations of stability was the effect of geometry competency. Also, the cross-sections presented in drawings were different in reality (Finnish Transport Agency, 2012; Andersson-Berlin, 2012).

Hasnayn et al. (2015) showed significant softening of subgrade arising from soil suction loss through wetting. Also, Bujnak & Wyrwal (2014) showed the design of high-speed railway assume overall geometrical parameters with proper ballasted track bed and bridge structure arrangement. The specific provision for the evaluation of dynamic impact includes vibrations, the riding comfort requirement, and actions by thermal forces. These affect the track modulus for approach to/from bridges.

Moormann et al. (2016) present track bed stability as of major importance for the safety and comfort of rail traffic. Quasi-static and dynamic loads from train traffic are supplied to the entire track system: superstructure, substructure and subsoil. The main objective was to detect mud holes in order to avoid costly interim or long-term treatment.

Connolly et al. (2016) observed wave propagation. When train speeds approach the velocity limits of the supporting track-ground system, track displacement can increase significantly. It is important to determine the speed at which these effects will occur. Researchers note that modelling the problem in detail can result in long run times.

Manzo Costanco et al. (2016) showed the major problems faced by railways at this moment. Ballast deterioration leads to high maintenance cost and is combined with the difficulty of obtaining high-quality aggregates. Problems generated by vibrations from train passage demonstrate the need for improved ballast.
Counter et al. (2016) show that global warming is probably responsible for unusual patterns of weather and specific weather events. These phenomena have affected the world’s railway infrastructure. Also, railways round the world are mainly constructed and laid on traditional granular ballast.

Train critical speed is an important issue related to high-speed train operation (Esveld, 1995). To pass the point of critical speed would lead to large amplification, which is unacceptable for railways in practice. This is the reason why present railway operations are all sub-critical. Wave propagation is also an important issue at transitions, such as between bridges and plain track. A gradual stiffness transition is desired to confine dynamic amplification. Based on the investigations of Esveld, especially in delta areas, such as in the Netherlands and in Japan, the subgrade often consists of weak soils with critical speeds far below the intended operational speed. In such cases, measures for increasing the vertical stiffness are unavoidable. Possible solutions include improvement, deep mixing, grouting, and piles.

Momoya et al. (2016) note improvement of degraded ballasted track to reduce maintenance work, where the ballast has not been replaced for several decades after the construction of the line.

The design of railway bridges is based on historical speeds of 160 km/h and need careful geometry design for construction (see RIL179). The thickness of ballast to the upper level of tracks using wooden sleepers is 450 mm; and in those using concrete sleepers, it is 550 mm.

Garinei et al. (2016) investigated a variety of technologies to reduce ground-borne vibrations near railway lines. Researchers point to an effort to define an optimised methodological approach for evaluating the reduction potential of mitigation techniques. The various mitigation techniques for train-induced vibrations may be used to evaluate how the vibration propagates through the structure of buildings. The purpose is to develop design guidelines for the prediction and mitigation of building vibrations.

Further to the above, Chen et al. (2016) developed an analysis of the improvement of fitting models. Predicting subsidence under high-speed railway lines. Researchers used four classical methods with both strengths and weaknesses. They found hyperbola fitting was simple but inaccurate and applied only under conditions with constant loads. Expanded hyperbola was the best fit
for the data in the embankment area, but showed higher errors than other methods. They found the three-point method easy to calculate but required high correlation. The Asaoka method was relatively easy to calculate but was not applicable in unsaturated soil layers. The result was to choose appropriate methods in unknown in situ soil and ballast conditions. The new land subsidence prediction model, which integrates the three-point and Asaoka methods, requires complex calculation procedures. Nevertheless, it can achieve significant improvements in correlation coefficients and relative errors. The researchers believed it would be highly applicable in the operational phase of high speed.

Alamaa (2016) investigated problems of high-speed railway embankments in Sweden, Germany, France and Spain, and found difficulties comparing criteria such as frost hazard, inherent ground quality, purpose of the railway (mixed traffic, solely passenger traffic, etc.) design parameters (life, axle load, etc.). Based on this, the research focused on trying to invoke typical Swedish conditions as follows: What thickness would the different design methods suggest for Swedish soils? How much impact does changing the axle to the axle load of a typical Swedish train have on thickness? Swedish soil, ballast material, typical axle load and speed, and traffic frequencies all need to be taken into account (see, for other countries, Serdelová & Vican, 2015).

Idea generation from soft soils to long span bridges to steel-beam guidance represents the genesis of the new steel-beam development.

### 3.2 The development of steel-beam structure and manufacturing

The purpose of this chapter is to provide an incremental move from idea generation to the development of steel-beam structure and manufacturing. Because of this, there is a need to initiate change and substitute old technology with new constructions of steel-based foundation technology (see section 1.1). Industries have not conducted major structural analysis regarding this substitution. Instead, much attention has been given in literature to the maximum or theoretical speed of trains and analyses of the transfer of passengers from place to place, etc. The steel-beam railway bridge technology is not only
meant to maximise the speed of trains, rather the main target is to find the optimal cost-saving solution of steel-beam design. It is also a target to enable trains to convey passengers and goods in many diverse types of geographical locations. This research presumes that concrete lines (see Fig.4) are not applicable. This is due to the large strength capacity of steel and the light weight of steel beam structure compared to concrete (RIL 179).

The idea of new railway design needs to include a steel-beam track foundation and piers. Moreover, railway bridges do not use reinforced concrete slabs or sleepers. In this work, the design connects two columns with steel-beam guidance to form a continuous bridge. The steel-beam guidance spans range can be varied from 20 to 60 metres. The length is not standard. The number of columns required is determined by the length of the span. A steel-beam guideway can be several kilometres long. It is not necessary for economic or technical reasons to use standard span lengths. The entire guideway system uses steel beams of varying lengths. New flexible manufacturing methods can manufacture different span lengths. A new foundation is constructed on a beam after beam, bridge after bridge basis.

Structural bridge design and the pretext for a particular construction method respective to a given project depends on the type of steel-beam guidance being assembled. To focus on cost minimisation through new steel-beam guidance procedures in assemblies on site, early calculations are required in the design process. According to Phelan (1993), bridge design is based primarily on 1) the method of support, and 2) standard span lengths with girders, etc.

This work is focused on steel-beam guideway structure and manufacturing. The steel-based train track foundation is the fundamental part of the new steel-beam bridge technology which supports the train and achieves the route alignment.

3.2.1 Transrapid’s design of guidance

The maglev transportation runs without wheel-rail contact. The main difference in comparison to classical railways is the realization of functions; their suspension, guidance and propulsion through magnetic fields; and high speed.
Individual steps were required to select routing options, prepare documents and to make procedures and decisions. Project planning and invitations to tender were made at the commencement of construction of a line section (see section 1.1).

They are highly sensitive to vehicle loading configuration and to vehicle speed. One difficult design issue is that no single vehicle length performs satisfactorily on the given beam at all expected maglev vehicle speeds (see the example of concrete provided by Huang et al., 2016), Fig. 4.

Fig. 4. Investigation of structure movements on the Shanghai concrete line, Huang et al. (2016) used a 24.768 m beam modelling, because the 24.768 m beam was the most-used type on the Shanghai line. The simulation model showed the maximum stress of the line structure under a rare earthquake of 9 degrees. The maximum stress takes place at the bottom of the pier column. In the case of a devastating earthquake, the plastic deformation occurs firstly in the pier bottom, at the same time deforming the plastic hinge and thereby resulting in the whole structure being overturned.

The guidance of Transrapid is originally designed as a steel bridge. According to drawings (FWG, 1998 b; 1998 c), all guidance includes various sizes of seams
to be welded in one beam length. Welding parameters are followed in every guideway. Transrapid drawings have been delivered to the author to consider automated manufacturing methods.

Planning procedure and organisation started in Germany in 1999 (Transrapid Milestones History in Germany, 2015). According to the drawing (FWG, 1998c), guidance includes 57 different positions of plate in sizes and thicknesses. The weight of guidance beam type I (2x31m) was 102.18 tonnes.

Steel plates used in this development, create the desired shape and greater height than rolled steel girders and are not limited to standardised shapes. A girder bridge is the most common and most basic bridge. Most of the bridges are designed to cross a river and have piers on both sides of a river (see, for example, Van Ness, 2017; Ates, 2011; Roger &Till, 2002).

The design of the German Transrapid guidance roughly appears to be based on the hull construction technology of shipbuilding. A ship can be flexible in tolerance on the sea. The designed flexible technology used for the maglev guidance is unsuitable. The high speed of a maglev train does not permit the guideway to incur a vibration effect. This was the reason heat input technology in T-beams, as used in shipbuilding, was investigated (see Fig. 5).

The capacity requirements were based on two standard guidance types. Guidance strength calculations are not presented. Capacity requirements for manufacture guidance were calculated weekly, monthly and yearly, which was seemingly a problem (Flessas, 2002; Kazanowski and Misiolek 2002). In designing capacity, the typical areas which need to be taken into consideration are guideway chamber, longitudinal gradient, vertical rotation and horizontal radius. These kinds of requirements are included in the production capacity calculations. Moreover, height of gradient; area of environment; wind; temperature; snow; and vibration criteria also need to be included in the same calculations. Further to this, the weight of a standard 2 x 31 metre guidance is 102.18 tons. In spite of the large weight, guidance needs to be produced within the right tolerances. The capacity requirements were based on two standard guidance types.

In charting the new branch (see Fig. 1) a clear gap in technology was recognised. The further development of new steel-beam bridge guidance was based on the observations above. Industry analysis gave an understanding of the
manufacturing problems – which agents are active in the maglev guidance beam industry (see Table 1).

3.2.2 Existing capacity for planned guidance

Referring to guideway technology in the USA, manufacturing depends on the design of a high performance system and refers to having a high operational characteristic to cost ratio. Phelan (1993) presents a narrow beam design with its structural design requirements (concrete reinforced primarily with steel), span length 25 m. Hybrid FRP (fibre-reinforced plastic) concrete reinforcing is a type of composite material. It can be used as tensile reinforcement in structural applications for maglev guideway design. The expected guideway beam loadings of a narrow beam design have a wind speed limit of 54 m/s. This results in horizontal distributed force of 14.71 kN/m, causing an eccentricity of 3.0 m from the mass centroid of the concrete beam, and a fully-distributed vehicle load of 19.61 kN/m, corresponding to a vehicle mass of 2.00 ton/m. Hybrid FRP rods were used to test the concrete T-beam form. For the first phase, one beam was cast for each of the three carbon thicknesses. The contact between the FRP reinforcing rod and the steel stirrups caused premature failure in the first test phase. These failures were attributed to the axial force from the stirrups, which caused shearing of the FRP rod under severe bending. In the second phase test specimens, stirrup and reinforcements in the concrete compression zone were mild steel with a diameter of approximately 0.476 cm. According to Phelan (1933) further research was needed in advanced material research, guideway beam dynamic analysis, opportunities for improving guideways, and large scale manufacturing processes. Moreover, research is still required to develop two or three approaches for automated manufacturing, simulate the operation of each approach to see which is more effective, and determine how much cost reduction can be expected from automated procedures.

Phelan (1993) suggested a structural system for bridge design including concrete and steel and, occasionally, wood and plastic. The design has a reinforced concrete section which uses pre-stressed tendons. The design
professional assumes pre-stressing materials are locally available, and local labour crews are familiar with the necessary construction procedures. Also, the researcher notes the importance of design process development. An adequate plan for transporting required materials to the construction site is also required. According to Phelan, basic bridge structural systems are girder (beam), arched (stone), suspension or cable stayed types.

Referring to international contacts from the year 1995 onwards (Table 1) – for example, maglev steel construction – Maglev Inc. (hereinafter referred to as “Company C”), plans were calculated for a guideway requirement of 400,000 tonnes of steel. Following the Transrapid maglev system, plates must be fabricated into uniquely dimensioned individual beams, most of which will be 204 feet long (62 m = 2 x 31 m guidance) and with a weight of about 135 tonnes with stators (weight of 62 m).

One suggestion in the meeting was alternative capacity for the German market to order some guidance by sea from Scandinavia. The need was to fabricate these unique guideway beams within specific tolerances. It was key to the success of the high-speed maglev to obtain two to five millimetres as tolerances.

However, meetings with customers revealed that there was not a single company with the capacity to manufacture guidance based on the original drawings (Flessas 2002). The general opinion was that the mass production needed to be created for maglev guidance production, such as a guidance “assembly-line” process, producing 20 beams a week, each beam with its own unique geometry, and all done in a cost-effective manner. These requirements have been the challenge facing engineers directly from the very beginning.

More problems arose when the German design of manual and/or robot made guidance was used in the USA (Flessas, 2002). Information received showed that there was a need to find another welding method for guidance steel-beam production.

Further to this, factory planned fabrication is key to achieving cost reduction, as in shipbuilding and other related fabrication processes for large components. The problem arose in the USA (Flessas, 2002), because existing steel plate fabrication shops were utilised. Even with unlimited time and money, only some guidance beams could be manufactured. There was a clear need for a new manufacturing technology with shorter time spans in relation to delivery time and current assets.
A steel mill testified that it would require large capacity when building 400 km of maglev guideway per year. The steel mill’s domestic plate production was full in supplying steel to the USA (Flessas, 2002; Burdett, 2015).

**Table 1.** Business contacts during development

<table>
<thead>
<tr>
<th>Type of industry</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Speed Train Industry</td>
<td>2</td>
</tr>
<tr>
<td>Ship Yards</td>
<td>1</td>
</tr>
<tr>
<td>High Rise Building Designer</td>
<td>1</td>
</tr>
<tr>
<td>Steel Material Industry</td>
<td>4</td>
</tr>
<tr>
<td>Concrete Guideway</td>
<td>1</td>
</tr>
<tr>
<td>Maglev Steel Construction Plans</td>
<td>1</td>
</tr>
<tr>
<td>Embassy</td>
<td>4</td>
</tr>
<tr>
<td>Maglev Factory Planning Company</td>
<td>1</td>
</tr>
<tr>
<td>Railway Traffic Service</td>
<td>1</td>
</tr>
<tr>
<td>Steel Construction Industry</td>
<td>7</td>
</tr>
<tr>
<td>Electrical Equipment Industry</td>
<td>8</td>
</tr>
<tr>
<td>Mechanical Industry</td>
<td>5</td>
</tr>
<tr>
<td>Machine Industry</td>
<td>3</td>
</tr>
<tr>
<td>Tools</td>
<td>4</td>
</tr>
<tr>
<td>Steel Bridge Project</td>
<td>2</td>
</tr>
<tr>
<td>Rail Embankment Projects</td>
<td>5</td>
</tr>
<tr>
<td>Railway Gateway</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>55</strong></td>
</tr>
</tbody>
</table>

In mapping technologies, the contacts were international companies (see section 3.1.1). Questions for the ship yard industries in the EU and USA focused on hull construction and its technologies; high rise building companies for towers and automated manufacturing in the USA; mechanical and machinery contract industries with offset programs in the USA, China, Korea, and Japan;
steel construction industries with customers in the Middle East; embassy contacts related to exhibitions in the USA, China, and Japan; and railways focused on concrete bridges and steel bridges in the EU.

This research did not have an ex ante questionnaire, but it looked at essential technical details of existing classical railway and steel beam manufacturing problems with the viewpoint of solutions. A new type of railway, such as the continuous steel-beam bridge, is a rigid construction bridge on steel piles – not only to cross a river, but also on land with soils such as soft soils and tundra, etc. (see steel piles: for example, RIL 95, RIL 90-1996, RIL 179; RIL 254-2016).

3.2.3 Distortion phenomena in welding

There are several problems in welding processes. One of these is distortion. However, based on the meetings (Table 1), steel-beam guideways create a huge demand for the global steel industry in “Company C”. Their problem was to get the design of guidance type (FWG, 1998c) within the tolerances by robot welding. They developed welding and weld distortion analysis on very large curved beams and shapes for final dimensions of the structures.

The supply problems were the same as with the Transrapid guidance manufacturing. The distortion problem was again present, resulting in many scrap beams. The same observations were made in Germany and the USA.

Based on the above, methods used both in the design of guidance and in manufacturing by robot do not overcome the effects of heating.

Bujnak et al. (2016) found a large number of steel bridges were built using rivets, due to inexperience and lack of knowledge about fatigue strength at the beginning of using welding techniques.

Okano et al. (2017) found distortion problems, because of the deterioration in dimensions and performances of structures. The same problem influenced the finished product’s appearance. Welded distortion is typically controlled by prevention or correction using mechanical and thermal techniques. It involves costly processing, which is additional to the welding process. In fillet welded T-joints, the angular distortion tends to be larger due to the shrinkage of the weld-
deposited metal. Similar effects occur with regard to the temperature gradient through the thickness of the welded plates.

Distortion is a common problem in welding processes. Advice on how to minimise some distortion effects are available in literature. Weld distortion results from the uniform expansion and contraction of the weld metal. Also, adjacent base metal during the heating and cooling cycle factors affect metal shrinkage. These factors make accurate distortion predictions difficult. As the beam is uniformly heated it expands in all directions. When the metal cools to room temperature, it contracts uniformly to its original dimensions.

To chart the new branch, the technology was divided into smaller parts of the guidance steel-beam structure. The steel-beam structure included a jig beam. Jig beams create a structure frame which needs to be straight, curved left/right or up/down in tolerances. To make heat input observations, this research used double T-beam-analysing phenomena. Separating double T-beams into two individual T-beams allowed observations of tension as well as energy impact and parameters.

The distortion tests were the starting point of the idea to manage energy input data, when shipbuilders Fincantieri (hereinafter referred to as “Company D”) and Alstom (hereinafter referred to as “Company E”) needed to use a holed T-beam profile in shipbuilding (see Fig. 11). The above test arrangement was used to investigate a solution for the distortion problem when developing maglev and high-speed rail guidance structures. This knowledge was important when developing a new steel-beam structure to eliminate distortion (see section 4.2.1).

3.2.3.1 Evaluation of distortion and welding vertically

In the vertical welding process in “Company E”, the welding points are on both sides of the vertical web plate. The method produces double energy input to the web plate. On the vertical welding line, one flange is first welded to the web from both sides at the same time. (See the Finnish Constructional Steelwork Association, 2001). If fillet welds in a T-shaped assembly are above the neutral
axis (centre of gravity) the ends of the piece tend to bend upwards (pulling effect upwards). If the welds are below the neutral axis, the ends bend down (pulling effect downwards), (The Lincoln Electric 1973). In the vertical web position, the girder has considerable rigidity. The sum of the energy input to the web plate is double compared to the horizontal position of web in the welding process.

Vertical welding lines are used in older shipyards. In several big cruise ship building process technologies (Hellgren, 2016), it was found that typical outcomes in the hull phase could lead to inefficiency. These was inadequate strength as well as vibration analysis and poor welding quality. Also, findings revealed delays in the production schedule and material delivery. Hellgren did not find the systematic energy input control in T-beam manufacturing.

The goal of the above test arrangements in this work was to reduce energy input to the web plate, which would allow observations to be made on how welds tend to distort and cause dimensional changes in the welding method used. The straightening of T-beams is a problem in large and continuous production. Straightening can become more difficult, causing extra unknown costs in production. More difficulties follow in achieving the correct tight tolerances.

3.2.3.2 Evaluation of distortion and welding horizontally

On the horizontal welding line, both flanges are welded to the web from the same direction at the same time in “Company B”. The deformations due to the welding stresses can be affected by the distances between the torches.

The horizontal web position is often preferred. Mechanised welding with two heads allows the flanges to be angled. Shrinkage forces will bring the angle of web-to-angle to 90 degrees in the finished piece.

When investigating alternative manufacturing processes and methods, it was important to find a solution for the German drawings. The design of the German drawings could not be manufactured by vertical, horizontal or robot welding,

Gap analysis led to the realization that there was a new need in the global market. The key technologies to develop are the new steel-beam structure with jig beam, horizontal manufacturing methods and energy input control.
3.2.4 Choice of welding method for guidance steel-beam structure

While searching for an effective welding method, the evaluation of energy input to both sides of web plate led to the conclusion that the horizontal welding method would be the best one to use. Another reason for selecting this manufacturing method was the need for large capacity in production. Manufacturing dimensional sizes of steel-beam products includes smaller and bigger sizes (see Fig. 10).

Charting welding technology of welded steel beams reveals that there are differences in welding methods. One difference in methods is when the beam is welded in place. An inclined fixture or the welding heads of a robot are moving in and to the welding points. In German-made guidance, welders or robot heads need to make a lot of movements. There are around 61 different seams in 31 metre guidance beams, which must be within the welding parameters (FWG, 1998 a).

The manufacture of various steel beams to specific specifications requires variable beam heights from minimum to maximum sizes. Alternative welding methods are single arc, twin arc, and tandem arcs. Different weld sizes and the test drive capacity of each line output could be analysed and planned. However, there are more development possibilities for horizontal welding line capability than the alternatives above. The choice was to develop the steel-beam structure by using the horizontal welding method. The choice of method in this work was different compared to German Transrapid and the USA (Kazanowski & Misiolek (2002).

A comparison was analysed at first between the two methods of horizontal and vertical welding lines. In a vertical welding line, the web plate is in a vertical position during the welding process. In a horizontal welding line, the web plate is in a horizontal position. Both welding line types use SAW welding.

Based on empirical testing, a horizontal welding line was chosen in which the steel beam moves (see Fig. 12).

After that, development focused on various points of view for the steel-beam structure(s) and strength capability. Recognising manufacturing capability was
included in the steel-beam structure(s) in order to evaluate steel-beam guidance development under factory conditions. Scaled sizes were chosen in charting the new branch of the planning process. In the manufacturing test, it is important to observe how distortion problems emerge.

### 3.2.5 Horizontal welding process

In a welded beam factory, plate parts of a profile beam are located in a storage unit when they are cut to selected sizes, and in an unloading and cutting unit when in roller shape. From storage, the plate parts are transferred to a conveyor. They are assembled to a crosscut profile of a finished beam through the aid of specific press rollers. From there, the beam is transferred to an assembly unit where separate plate parts are joined (see section 1.1).

The horizontal welding line allows fast pre-settings of the equipment when the size and profile of the beam need to be changed. Every adjustment of the equipment is partly determined by the size and profile. The jig beam can be operated at a centralised control panel on a control unit. A separate alignment unit is used for the adjustable rollers for inspection and calibration of the profile of a beam.

Horizontal welding line equipment consists of an automated method for joining separate plate parts into a jig beam. The advantage of the welded profilebeam compared to the hot-rolled beam is that the same strength values can be reached with lighter construction beams. The required strength value in a hot-rolled beam is suitable for oversized construction, due to the rolling method. The horizontal method used in this work supports the possibility of producing highly precise sizes. Altogether, the manufacturing method was used as a research instrument for developing new steel-beam profiles as follows:
1. An assembly conveyor and press rollers which can simultaneously handle three or four separate plate parts, from which a beam will be produced.

2. One or two assembly units, which can have beam-moving rollers equipped with regulators to adjust speed, plate parts supported by automated adjustable rollers, equipment to join the seams of the plate parts which can be welding equipment, and automated adjustable rollers which increase the strength of the beam and enable the optimisation of the beam qualities.

3. A transfer conveyor for transferring a beam.

4. An alignment unit comprising of self-adjusting and adjustable rollers for inspection and calibration of the beam profile.

The evaluation of welding processes contributed to an understanding of the new manufacturing method and solutions for the steel-beam railway bridge guidance design.

3.3 Mechanical performance of the selected beam profile compared to I-beam and box-beam profiles

After considering an effective welding method for the guidance steel-beam structure, the research focused on the evaluation of conventional welded I-beam and box-beam capabilities from a mechanical performance perspective.

Regarding steel-beam railways, there is a need to create and develop new steel-beam bridges to reduce lateral oscillations. The speed of high-speed trains, maglev trains and heavy loads affect snaking. Bending force is used to analyse the weakness or strength of profile structures when making observations of I- and box beam strength (see Fig. 7).

The bending test also recognises the strength of submerged arc welding. Weakness tests (= weakest axle in the co-ordinate system of members) eliminate weakness for the steel-beam structure. The identified weakness of I- and box-beam profiles support the other axle strength capability for steel-beam guidance.
Destructive testing is mainly used in the welding and procedural tests, and they do not actually belong to the daily inspection activity. The test was selected as the only method to obtain a knowledge of shape weakness and strength capability in order to compare calculations (See the Finnish Constructional Steelwork Association, 2001; RIL 90-1996).

### 3.3.1 Strength and weakness tests on existing I- and box-beam profiles

The analysis of co-ordinate systems of members supports the need for a solution for steel-beam guidance and a manufacturing method for this new profile. The tests of the mechanical performance of profiles and manufacturing systems included four stages in this work:

1. Test by hydraulic bending unit, I-profile bending capability roughly in z-z axis; supposed: I-profile strength in y-y axis acceptable.
2. Test by hydraulic bending unit, box-profile bending capability roughly in y-y axis; supposed: box-beam profile strength in axis z-z acceptable.
3. Test by hydraulic bending unit, a beam-type profile bending capability designed by I-profile strength capacity in the y-y axis and box-beam profile strength capacity in the z-z axis.
4. Defect tests in welding system when manufacturing items 1–3.

The design method was based on analysis when substituting the weakness of I-beams with the strength of box-beams and also when substituting the weakness of box-beams with the strength of I-beams. Destructive testing is mainly used in welding and procedure tests. They do not actually belong to the daily inspection activity in the workshop (see Salokangas 1975; the Finnish Constructional Steelwork Association 2001).
The I-beam strength/weakness capacity was tested from the point of view of bending strength. A bending machine includes: a machine bed, stopper, profile to bend, bending cylinders, laser-light and measuring equipment.

A selection of scaled beam shapes and sizes (see Fig. 13), could be found to be useful to investigate problems in I- and box-beams. Tests focused on the observation of the I-beam weakness axle in the bending test (Fig. 5).

Fig. 5. A conventional welded I-beam structure weakness test. Bending was made in the z-z axis direction. The bending unit included two (2) moveable carriages with bending equipment, and a stepless speed control with joystick for both carriages. Bending equipment included a hydraulic bender in both carriages as well as joystick-controlled bending cylinder movements for both carriages.

Observations were made for jig beams regarding ultimate tensile strength when the I-beam was broken. It was central to get strength data pertaining to one beam with regard to technical threshold values. It was also imperative to look at the objectives for the idea’s structure, and to focus on decisions to develop the newly idea for application in steel-beam railway bridges.
There was a need to create and develop new steel beams which were resistant from vibration caused, for example, by a horizontal earthquake (see Huang et al., 2016; amplification ratio of common and rare earthquake in Shanghai line). Existing methods were used when considering a new steel-beam structure simulated by linear beams (Fig. 5). The bending test recognised the strength of submerged arc welding together with steel plates. The test can be used as an important criterion when designing steel-beam guidance.

Experimental manufacturing observed box-beam weakness to energy input and a conventional box beam that needed to be straightened after the welding process. Tests focused on the observation of the box-beam weakness axle in a bending test (Fig. 6).

**Fig. 6.** Welded box beam structure weakness test when two hydraulic cylinders press beam in its 1/4 measurement points.

Because of observed weaknesses, I- and box beam shapes were substituted by the new structure of the beams.
3.3.2 Preliminary bending test of beam structure

A strength test was conducted in accordance with the beam structures. The bending test was based on a method which sufficiently recognises a profile weakness. The test was made with a scaled method using various constructions and materials. In this work, the supposed beam profile function is linear to the buckling of the plate for larger-scale use. A scaled test is the only way to calculate the higher strength of guidance.

For this work, a test was used from the perspective of a piece’s co-ordinate systems, which are the x-x, y-y and z-z axes. The above test revealed that I-beam strength is weak in the z-z axis (see Fig. 5) but strong in the y-y axis, because it is possible to use larger new manufacturing methods for higher I-beams (Fig. 7).

![Fig. 7. Co-ordinate system of a member in Figs. 5 and 6 (EN 1993-1-1 Eurocode 3).](image)

The Autodesk Robot Structural Analysis Professional Program was applied to the preliminary calculations (Hauta-aho, 1993), and later to investigate the properties of the new profiles. The experimental use of the program pointed to its application for calculating the preliminary cross-sectional properties for the three profiles. Section analysis of the three new guidance steel beam structures could be calculated based on geometry description at characteristic points of profiles (in the y and z axis). Here follows the analysis result parameters: general
results as area, centre of gravity, shear centre, base material and principal system as angle, moments of inertia, sectional moments of inertia, maximum distances. Higher $I_z$ leads to higher lateral stiffness.

Investigation of box-beams revealed that the beam is weak in the vertical position in the $y$-$y$ axis (see Fig. 6), but seems better in the $z$-$z$ axis (see Fig 7). This means it is a suitable characteristic for developing steel beam guidance. In any case, box-beam weakness needs to be supported by I-beam characteristics in the $y$-$y$ axis, but how?

How would it be possible to manufacture new beam types when the weakness of a tested beam has to be substituted by the strength of another one? This is not easy from a manufacturing point of view. It concerns the question of a new type of beam, which cannot be manufactured manually.

Three new steel-beam structure types could be constructed. The bending capacity was calculated by the Autodesk Robot Structural Analyses Professional program, which calculates strength values.

The geometric characteristics of the test beam are based on ratio $B/H$, where $B$ is the width of the upper level flange and $H$ is the height (FWGMagnetschnellbahn Fahrweggesellschaft mbH, 1998 c).

### 3.3.3 Performance requirements for a new manufacturing method

It was important to understand the forces driving steel-beam guidance, but also to assess how the manufacturing methods can be developed for new steel-beams resistant to snaking.

One important criterion was machine capacity when the process presses the plates together. Welding plates (the beam moves) form structures by using submerged arc welding. Horizontal welding lines have the capacity to increase the press force of the flange plate in accordance with the jig beam specification (See Fig. 12).

The bending test recognised the strength of submerged arc welding. Pressing increased the strength of steel beams more than that supposed, due to the three
web structure. The above test can be used as an important criterion when designing solutions. The identified weaknesses of I- and box-beam profiles create a strong new capacity for steel-beam bridge guideways.

The new capability of the welding line included sophisticated logic programs to control moving rollers. The new beam structure was equipped with operations for higher welding speed regulation. The equipment joins the seams of the plate parts, and automated regulated rollers enable the pre-stressing features. Jig beams are manufactured in the horizontal position. There are many applications when considering the best structure for large steel-bridge foundations.

This work used a factory’s heavy type horizontal welding line. Mechanised solutions to evaluate the important characteristics needed to design and develop the product, structures and manufacturing method were applied. The process generated design values for a new product, manufacturing values for the new method and values for new manufacturing.

The welding line need the capability to manufacture I-beam to jig-beam: two welds at the same time. The welding line also requires the capability to manufacture a box beam with a jig beam. For that, four welds are required at the same time. In total, the steel beam involves eight welds, creating new performance.

Two different welding lines needed to be constructed to manufacture the steel-beam bridge guidance. The steel beam required a new construction in manufacturing. Using the above manufacturing method, the new steel-beam structure with side plates at angles of 45°-90° could be manufactured and tested.

The requirement for the new type of welding line included the development of an energy input control system in the new lines. This was due to tolerance requirements based on structural steel-beams, regulations pertaining to static rather than dynamic loads. This is because steel-beam bridge guidance needs to be manufactured in accordance with the dynamic load tolerances caused by moving loads.

The technical need for steel-beam strength resistant to lateral oscillations effects is at its greatest in earthquake situations. Based on varying environmental requirements, a new steel-beam guidance type can be calculated for different applications by co-ordinate systems of members in the x-x, y-y and z-z axes.
3.4 Energy measurement during welding enabling the manufacturing project to be tracked and possible corrections to be made to the beam

The energy input problem arose from experiments at factories A, and B with shipyard “Customer D” and “Customer E”. Also, Transrapid communicated distortion and tolerance problems. In one guidance they used 61 different welds in one 31-metre guidance. The total number of welds was much more in comparison to shipyards. Manufacturing was based on welding parameters changed at every welding point. Consequently, there are too many welding parameters to manage. This work employed the submerged arc welding procedure (SAW), as used in shipyards.

3.4.1 New manufacturing process

The new manufacturing process is planned for energy input control for smaller tight tolerances during processes.

Podder et al. (2014) found that, when using the tractor type welder, any change in dimensions causes a significant change in the resulting thermal profile. Further to this, these heat source models as well as the respective parametric dimensions vary, depending on the welding method. They also state that these dimensions were chosen for each and every particular case simulation with a given welding situation.

This work did not use the tractor-type welding method (groove welding), but rather the horizontal welding line method, in which the beam moves. The energy input control system recognises the parameters of each jig beam and steel-beam structure. The system has the capability to measure, for example, the straightness of upper and lower flanges of jig beams and calculate the energy input values in accordance with beam length.
3.4.2 Measuring tight tolerances of the jig beam

The jig beam is an important part of the steel-beam structure and creates potential for straightness tolerance, up/down tolerance, left/right tolerance. With regard to railway bridges, the capability of the jig beam is an important criterion. The jig-beam strength keeps one instance of guidance in geometry.

Energy measurement is based on a tight control system during welding, which has been developed for the beam structures. The horizontal welding line uses SAW welding in manufacturing. The middle web with seams uses various throat sizes at the bottom and top flanges. The edge webs may also be connected to the bottom flange with one or more seams. It may be connected to the top flange with one or more seams, depending on the web thickness. The middle web, upper flange and lower flange thickness can be differing sizes based on the strength calculations.

When joining plate-like parts together with SAW welding, the welding point(s) generate energy through the welding blowpipe to the welding site and seam. This energy and/or other measurable quantities may be measured from each seam, or from one or more welding points of a seam. During welding it is possible to measure the energy input to the seam, the energy generation value, or a quantity directly or inversely proportional to the input energy. The measured value may be the heat input or energy per unit of length. Thus, the value may be kJ/mm, (see Fig. 8).

The tolerance must be precise when manufacturing a steel-beam guidance for a foundation. Therefore, two important manufacturing criteria of the steel beam are the vertical and horizontal curvature tolerances. These can be measured and compensated for. The steel beam must be manufactured accurately, in accordance with its preferred method. When put into practice, the warping problem with respect to the steel beam can be solved (see Fig. 8).
Fig. 8. The energy input control system in the SAW welding procedure. The idea of the jig beam refers to the central web of the rail beam of the magnetic train; it is the mould, positioning mould, or fasteners according to which, or supported by which, the beam or a part thereof can be made. A jig can also refer to the shape or mould of a three-web beam, to which the beam is set in a first step so as to make the rest of the beam in a second step. The jig may be an H-beam or H-portion, or the H-jig serves as a mould once the side plates are added. The central web may also be perforated. The internal jig may be symmetric or asymmetric.

Figure 8 shows a method for manufacturing a beam. A welding machine a) welds the seam of the beam. The energy input system into the seam, can be measured with a sensor b). In the system of c), a measuring device d), and the sensor data may be fed into the measuring device and on to an adjusting device e). The readings of the adjusting device and measuring device can be read on a control panel f) that may also set control values for the adjusting device, measuring device, and welding machine.
3.4.3 Measuring the tight tolerances of the beam structure

The energy input measuring system is a method used in the manufacturing of beams. The energy input control system is a part of the further development of the new branch. This phase involved a lot of testing, such as energy input measurements in all seams, some seams, or none at all.

The control system was adapted to keep the energy values either exactly the same or substantially the same. An alternative setup allows the energy amount input into the welds to be substantially the same in one seam, or different in value in at least one other entire seam or part thereof.

There was a need during welding for the values of the welding parameters to be readable from a control panel on the assembly equipment. The control panel was also used for measuring the energy of heat input. The input of thermal energy can be measured, and the allowed and selected values monitored. Also, each seam was visible on the display in the assembly equipment system.

The control panel displays control data when the I-beam is moving forward along the beam’s whole length (L). The steel-beam structure has at least eight longitudinal welds. After the eight welds are controlled and accepted, the energy measurement system saves the data and, if required, sends the data for the parameters of each welded beam to the office, designer and/or customer.

If the parameter values are changed, thermal energy makes it possible to synchronise the warping of the beam by welding points during manufacturing. The input of thermal energy can also be measured with separate sensors. The assembly equipment can compare a signal received from a sensor with one or more predefined threshold values, limit values and/or another measuring value. It can also adjust the energy or power being supplied on the basis of the measurement and comparison. It is possible to control the manufacture of a rail beam in the system in accordance with the tolerance requirements of the rail beam. The value of the energy supplied to the seam or the maximum value of heat input can be obtained from the material specifications for various steel grades for the SAW welding procedure.
The energy value input into each weld or part thereof can be measured and adjusted individually. Alternatively, the adjustment may be simultaneous. It is possible to use an energy input synchronisation device or the assembly equipment’s measuring system, which measures the amount of energy input to each weld.

Seam-specific parameter information may be provided for various seams in order to control the method and measurement received through sensors. For example, the cutting parameters of the plates may cause warping. This warping may be compensated (See Fig. 5). Warping may also be caused by a controlled energy input synchronisation device in the manufacturing steel-beam method (Fig. 8).

**Summary of Chapter 3**

Gaining an understanding of the manufacturing environment rests on the idea of the generation and related requirements of steel-beam foundations. Classical foundations have a lot of parameters, which result in factory-made new steel-beam guidance being competitive with classical foundations. Development of the manufacturing method and steel-beam structure is an experimental process directing the welding system, where the beam is moving.

Classical foundation technology has problems resulting from soils, soft soils and damp soils for both high-speed rails and the increasing mass of freight. There is a need to investigate the problems of classical railways, which have been presented from the new viewpoint of steel-beam railway-bridge. The development of steel-beam structures and their manufacturing take the requirements of maglev and high-speed rail into account. These include evaluations of distortion, the welding process, mechanical performance, tests of present profiles, and the new profile co-ordinate system. Energy measurement during continuous welding with possible corrections in manufacturing a beam is an important factor. The method includes the development of the new branch and focus on a competitive steel-based track foundation.

As Chapter 3 showed, the classical railways foundation technology is old and partially outdated for high-speed technology. According to Porter (1990), the
progress of work in an industry can be shown by closely examining the industry over time. This leads to an understanding of the process by which it emerges in a nation and achieves as well as sustains international success. Development occurred in this order: early mechanisation, steam power and railways, electrical and heavy engineering (see Kondratieff, 1935 in Trott, 2008; in Lahti, 2015).

The cost-saving technology in manufacturing steel-beam railway bridges in this study is useful with regard to wheel-rail contact. As railways are many kilometres long, multiple cost savings are possible when designing steel-beam bridges for HSR. The railway steel beam is a solution for classical railway problems. It is possible to use piers of steel over varying soil types (See RIL 254-2016; Mylonakis et al., 1995; Gao et al., 1998; Kawashima et al., 2000; Yougberg et al., 2004; Nelson et al., 2007; Deb, 2008; Aygün et al., 2011).

In steel-beam railways, the vertical parts provide the structure with vertical rigidity and transmit forces in the top flange to the bottom flange. The bottom flange is the foundation of a structure, structural element, or structural entity. The horizontal parts provide the beam’s horizontal rigidity.

Many technological problems had been investigated in embankments with regard to soft damp soils. Problems arise from the use of concrete sleepers in classical construction, especially when using sleepers in embankments for higher-speed rails. Old classical embankment construction is an obstacle for future railway technology (see Manzo Costanzo et al., 2016). A comparative calculation of cost savings can be performed between classical railways and the continuous steel-beam railway bridge.

The reasons why concrete beams were used in Shanghai was based on a lack of suppliers for the steel-beam solution. Suitable steel-beam welding technology was not available when the construction decisions were made. Based on Chinese market analysis in 2001 (China Embassy in Table 1), there was a need for a new steel-beam manufacturing technology. In China, an inclined fixture was in use. During the same year, the decision was made to use reinforced concrete for the guideway.

Earthquakes were not well-considered in the design of the guidance, due to the fact that few earthquakes occur in Germany. Later, Huang et al. (2016), investigated the influence of earthquakes in line constructions with regard to heavy concrete guideways and piers.
The reaction of the guidance structure could be analysed. Researchers used the most common beam model of 24.768 m with a five (5) span model, when simulating the whole concrete line. The Shanghai line contained five (5) spans, meaning six (6) piers (Fig. 4). The simulation results found the pier bottom became the weak point of the entire structure under the load of an earthquake, when regarding the limit of carrying capacity as seismic fortification standards. The standard regulates steady vibration, shock vibration and random vibration in the definition of z-level vibration (ISO2631/1-1985). A human can just feel weak and strong vibration the body cannot stand. Moreover, vibration acceleration changes up to a million times (Bi et al., 2016).

Tests for classical rail ballast lateral strength value resistance do not exist. Some tests of lateral displacement caused by lateral force/sleepers have been performed (Zand & Moraal, 1997). One result reached for lateral resistance without both longitudinal and vertical load and its curve-fit approximation. The lateral resistance track in ballast showed: 8 kN lateral force/sleeper cause lateral displacement 200 mm.

The result of this work provides the assumed behaviour with some characteristic points for lateral resistance force and deflection. The relationship between the peak lateral resistance and the minimum lateral resistance was linear. The researchers noted tamping operations already damage the ballast and fragment concrete sleepers. Based on the research, classical railways have a very low lateral resistance.
4. RESULTS

4.1 Competitive designs of steel-beam guidance structure

In order to study the steel-beam cross-sectional properties in relation to classical foundation technology, a new design of the steel beam guidance and manufacturing method is required. A literature search does not reveal the parameters for a comparison with the new steel-beam design. The steel-beam structure has a very large $I_z$-value for competitive design.

The steel-beam railway bridge is a solution to manage and control the construction of HSR’s. The steel-beam has longitudinally welded seams. A large structure can be manufactured for a large foundation. The steel-beam railway bridge provides many advantages to architects and engineers in finding a suitable geometry and possibilities such as quantity, material choice freedom, material width and thickness, the freedom to choose steel quality, and for varying steel quality in the same section. The capacity of the steel beam in terms of production and delivery time is short. It does not depend on finding suitable solutions when changing beam sizes and renewing existing structures. The manufacturing and steel beams create cost savings for railway bridges. An alternative beam or beam profile should meet the conditions of the following model.

The following **input data is utilised to calculate** the HSDA beam properties (see Fig. 11, note “−” represents the way to feed the data, not an operator):

$$HSDA = H \times \frac{d_1}{\alpha d_2} – t_1 \times \frac{B_1}{t_2} \times B_2 - L,$$
where HSDA = a dynamically loaded three-web slant-webbed A casing, H = the total height of the middle web, bottom beam and top beam or the height of the profile from the bottom surface of the bottom flange to the top surface of the top flange, d1 = the thickness of both edge plates, d2 = the thickness of the middle plate, t1 the thickness of the top flange, t2 = the thickness of the bottom flange, B1 = the width of the top flange including the thicknesses of both edge plates or the width of the top part of the profile, B2 = the width of the bottom flange or the width of the bottom part of the profile, and L = the length of the bottom flange and top flange and web or profile. A structurally correct and accurately dimensioned beam should meet certain requirements.

An alternative is that the beam or beam profile should meet the conditions of the following model and **input data is utilised to calculate** the HSDQ beam properties:

\[
\text{HSDQ} = H \times \frac{d1}{d2} - t1 \times \frac{B1}{t2} \times B2 - L
\]

where HSDQ = a dynamically loaded three-web Q casing; H = the total height of the web, bottom beam and top beam; d1 = the thickness of the edge plate; d2 = the thickness of the middle plate; t1 = the thickness of the top flange; t2 = the thickness of the bottom flange; B1 = the width of the top part of the profile or the width including the thicknesses of both edge plates; B2 = the width of the bottom flange or width of the bottom part of the profile or width of the profile; L = the length of the top flange and bottom flange or profile.

The beam may also be called a casing. Dynamic load refers to the fact, in addition to the static load used in conventional construction, that the beam withstands traffic loads, earthquake loads, impacts, etc. A beam withstanding dynamic loads withstands a moving load better than a construction beam dimensioned for static loads. A beam according to its preferred implementation may withstand static and/or dynamic loads.

In addition, an alternative beam or beam profile should meet the conditions of the following model, and **input data is utilised to calculate** the HSDK beam properties:
HSDK – H x d1/d2 – t1 x B1/t2 x B2 – L,

where HSDK = a dynamically loaded three-web K casing, H = the total height of the web, bottom beam and top beam or the height of the profile from the bottom surface of the bottom flange to the top surface of the top flange, d1 = the thickness of the edge plate, d2 = the thickness of the middle plate, t1 = the thickness of the top flange, t2 = the thickness of the bottom flange, B1 = the width of the top part of the profile or the width of the top flange, B2 = the width of the bottom flange or the width of the bottom part of the profile or the width of the profile, and L = the length of the top flange and bottom flange and web or profile.

The length L of the steel beam may in all cases be 5 m, 16 m, 32 m, 50 m, or 64 m, for example. The length of the beam may be optimised to be as long as possible. The enclosed beam HSDA solutions were compared to concrete beam (see Fig. 4 and 9) and the comparative cost difference calculation with classical railways (see Tables 22 and 23).

**Fig. 9.** HSDA steel-beam structure solution for long span bridges (see concrete type in Fig. 4)
Fig. 10. HSDA dynamic loaded three web steel-beam bridge possibilities in mm.
Welded profiles are normally made of S355 grade steel. Steels of S420 and S460 are also used. Eurocode 3 cannot be applied in the design if use of high-strength steel is intended. Lower grades than S355 are not normally used to fabricate welded profiles (see the Finnish Constructional Steelwork Association 2001).

In this work, the developed steel-based railway track foundation / steel-beam bridge provides an important cost-effective solution. The steel-beam structure eliminates problems to do with classical railway ballast and sleepers, etc.

4.2 Testing the manufacturability of the new steel-beam design

When designing steel-bridges, the most common beam type is the I-beam. The Transrapid had guidance with many cross stiffeners inside the cover plates needing to be welded. The designed construction allowed waving in the same manner as for a ship, but in the steel-beam railway bridge, waving and vibration should be eliminated.

The distortion does not only appear in shipbuilding. In 1998, the Transrapid design with technical specifications of two maglev guidance was analysed. Unaware of the above shipbuilding history, this work started to look at the steel-beam from the distortion perspective. This was due to the crossed stiffeners inside the guidance being formed in a T-shape. T-shapes are still used in shipyards and are welded conventionally by a vertical welding line.

In seeking a solution for steel-beam guidance, the T-beam test guided the start of the development of the beam structure. It is an empirical fact that T-beam manufacturing creates the most distortion problems in “Company D” and in “Company E” (See Fig. 5).

The first test in designing the new guidance was T-beam manufacturing. The aim of using T-beams in this work was to analyse web plate vertical distortion, web waving, beam camber and beam curvature. Difficulties were observed with these issues that could be used as a solution for the guidance beam. Difficulties were incurred to make T-beams straight. Data for the extra time used is
important when straightening is required. It is also important to recognise how much time T-beam straightening requires as a result of heat input.

4.2.1 Testing guidance jig-beam rigidity

The general technical instruction in process test execution was in accordance with standard SFS-EN 288-3, SFS-EN ISO 9001, EN1993-1-1 Eurocode 3. The general technical instruction included:

1. selection of materials and welding additives
2. selection of welding parameters
3. the welding proof: welding parameters are measured during the proof and recorded. If the working temperature is increased, it is performed in accordance with the instruction, and the results are recorded
4. in testing, the test pieces are approved by the quality inspector of “Company B”, “Company D” and “Company E”
5. welding energy, an important criterion in this test.

A vertical welding line was not used in developing a jig beam for steel-beam guidance for the following reason: the distortion problem could be empirically identified when manufacturing T-beams in the shipyards, and because of the problem of too much energy in vertical line weld points, which could be calculated as a sum of energy (Table 2 a), (see also MET, 10/86). Formula in Table 2 b used.

Table 2. Energy input differences in vertical and horizontal welding line weld points.

<table>
<thead>
<tr>
<th></th>
<th>a) Vertical welding line</th>
<th>b) Horizontal welding line (see Table 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q )</td>
<td>( \frac{60 U I}{1000 V} + \frac{60 U I}{1000 V} )</td>
<td>( \frac{60 U I}{1000 V} )</td>
</tr>
</tbody>
</table>

where,

\( Q \) = welding energy (kJ/mm),
\( U \) = arc voltage (V),
\( I \) = welding current (A),
\( V \) = the welding speed (mm/min).
On a vertical welding line, one flange is first welded to the web from both sides at the same time (causing + energy input to I-beam web), after which the I-beam is turned around and the other flange is welded (causing + energy input to I-beam web).

T-beams are exposed to a longitudinal mechanical bending during the welding operation, during which they are produced on a vertical welding line. An important target of this work was to control the energy input for steel-beam railway bridge tolerances. In a horizontal welding line, the energy input to the web plate is only half the sum of energy Q in Table 2. Both flanges are welded to the web from the same direction at the same time in the single and twin arc method.

Further to this, the cooling rate may be low in very thick plates, which may lead to the properties of the steel not meeting the minimum specification’s cooling rates. When using larger plate mass, the weld area in a thick plate cools more rapidly compared to the weld area in a thin one. Welds are subjected to rapid cooling rates, which frequently induce high stresses and lead to cracking. In welding, the cooling rates of thin and thick plates are opposite.

Referring to Cho et al. (2015), the researchers found constant heat input when investigating flux consumption and metal transfer for the tandem submerged arc welding process. The variation in the current of the leading and trailing arch can have a complex impact on the flux consumption rate. A detailed analysis of process parameters is critical for better understanding of the weld quality. Also, with regard to variation in relation to the process parameters, the researchers note that there is little corresponding research on the SAW-T process (see also Kiran et al., 2014).

This work did not use the SAW-T process following experimental projects at factories A and B, where the tandem arc large-energy input caused distortion. Consequently, SAW welding with single- or twin arc wire was used (see Submerged Arc Methods in MET, 10/86).

Calculation by formula (1) is only approximate because the heat losses can be large. The formula was found to be sufficiently accurate to predict the maximum allowable heat input for a given set of conditions.
The prediction and minimisation of angular distortion are important technical issues for fillet-welded T-joints. The enclosed distortion effect test was used in this work (Fig. 11).

**Fig. 11.** Distortion effect test arrangement on a double T-beam, where the beam is separated into two T-beams after horizontal welding. The T-beams were manufactured in the horizontal position of the beam web to investigate the energy input effect, instead of welding in the vertical position of the beam web, as used in shipyards. Technical specification: Assembly Conveyors Type 1600 Welding Unit, Transfer Conveyor, Flange Alignment Station and Receiving Conveyors. The test used pre-heating during welding to make observations of distortion in SAW welding.

The enclosed welding parameters used in the test (Table 3) are as follows:
WPAR (Welding Procedure Approval Record) no. 9551 testP1; no. 9551 testP2; no.9551 testP3; no.9551 testP4; no. 9551 testP5; no. 9551 testP6; no. 9551 testP7; no.9551 testP8; no.9551 testP9; no. 9551 testP10 – in total, 10 beams tested.
<table>
<thead>
<tr>
<th>Test of jig beams</th>
<th>I (A)</th>
<th>U (V)</th>
<th>V mm/min</th>
<th>Q kJ/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam P1 pass 1</td>
<td>660</td>
<td>29</td>
<td>1090</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>680</td>
<td>26</td>
<td>1200</td>
<td>0.89</td>
</tr>
<tr>
<td>Beam P2 pass 1</td>
<td>660</td>
<td>29</td>
<td>1090</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>680</td>
<td>26</td>
<td>1200</td>
<td>0.89</td>
</tr>
<tr>
<td>Beam P3 pass 1</td>
<td>720</td>
<td>27</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P4 pass 1</td>
<td>720</td>
<td>27</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P5 pass 1</td>
<td>720</td>
<td>27</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P6 pass 1</td>
<td>720</td>
<td>27</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P7 pass 1</td>
<td>720</td>
<td>26</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P8 pass 1</td>
<td>720</td>
<td>27</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P9 pass 1</td>
<td>720</td>
<td>27</td>
<td>1120</td>
<td>1.05</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1120</td>
<td>0.98</td>
</tr>
<tr>
<td>Beam P10 pass 1</td>
<td>720</td>
<td>27</td>
<td>1600</td>
<td>0.72</td>
</tr>
<tr>
<td>pass 2</td>
<td>700</td>
<td>26</td>
<td>1600</td>
<td>0.68</td>
</tr>
</tbody>
</table>
The test in this work used the idea of a double T-beam form: a laser cut web plate with holes in the web, and pre-cut in the middle but holding a small area fixed for the horizontal welding line process (see Fig.11). The pre-test of the jig beam used holed webs (the original idea for the jig beam was a lighter, holed one). The results showed distortion appears better in scaled guidance steel-beam sizes. The welding line chosen was mainly for smaller beam sizes (H < 1000 mm). In this welding line, the flanges are pressed against the web hydraulically, with the pressure force being adjusted in accordance with the size of the beam. The holed beam was welded in a horizontal position and the fillet welding of both flanges was performed simultaneously. The beam tolerances were measured after welding (see Table 4).

A tentative procedure was created as follows: the test welds included pre-heating, adjustments of welding current, voltage and welding speed. The test for distortion was made using the location of the welding torches on both sides of the web. In this way, energy input could be minimised. The choice of the horizontal welding method resulted in the possibility to minimise the risk of cracking. When investigating the distortion problem by using the most critical T-beam welding, the distortion problem was very complicated, resulting from holes in the web, (test excluded T-beam strength tests). The technical data for the test beams is as follows:

- material Fe 42B-non (S275JR)
- hot-rolled flange plates 10 x 100
- web plate 8 x 880 mm with holes,
- weld sizes 3.5 mm,
- beam length 5,600 mm,
- twin arc welding method, and
- heating by acetylene gas.

In testing, the material strength effect on shrinkage and distortion Yang et al. (2014) found out-of-plane distortion increases as heat input increases. The effects of material strength and heat input on in-plane shrinkage and out-of-plane distortion were studied by welding and measuring 44 small-scale panels in
the laboratory. As the welding heat input increases, shrinkage and distortion are increased for both lower and higher strength materials.

Shrinkage cannot be prevented, but it can be controlled. To minimise distortion, methods must be employed both in design and in the workshop to overcome the effects of the heating and cooling cycle.

Podder et al. (2014) tested heat source parameters where the welding speed was at a very low level (0.3 – 0.8 m/min). The welding speed was 1.12 m/min with a material thickness of 8 mm. Consequently, a tractor welder could not be used in the energy input test.

In testing distortion control by welding with trailing reverse-side flame heating (Okano et al., 2017), researchers found distortions vary drastically depending on whether trailing reverse-side flame was performed. The plate was inclined at a 45-degree angle in each welding pass, in order to maintain a flat welding position at all times. The equipment used a very old system and manual welding type, in which the only way to eliminate distortion was by heating. There was lower-side welding on the 1st pass, after the 2nd pass, on the upper side on the 3rd pass, and after the 4th pass. These were the welding directions and the sequence in the fabrication process of the plate girder which caused distortion.

The test used web pre-heating during welding to make distortion observations (see Table 4). The test also analysed the effect of lateral curvature for the steel-beam structure. The test used pre-heat in different areas at a distance of 0 mm, 10 mm, 30 mm and 50 mm on both sides of the middle of the beam.
Table 4. Test of camber in product level

<table>
<thead>
<tr>
<th>Test beam</th>
<th>Pre-heating points</th>
<th>Lateral curvature Dimensional tolerance L/1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam P1</td>
<td>+/- 0</td>
<td>5-6 mm</td>
</tr>
<tr>
<td>Beam P2</td>
<td>+/- 0</td>
<td>0-5 mm</td>
</tr>
<tr>
<td>Beam P3</td>
<td>30 mm to left; 30 mm right</td>
<td>5-6 mm</td>
</tr>
<tr>
<td>Beam P4</td>
<td>50 mm to left; 50 mm right</td>
<td>+/- 0 mm</td>
</tr>
<tr>
<td>Beam P5</td>
<td>10 mm to left; 10 mm right</td>
<td>3-4 mm</td>
</tr>
<tr>
<td>Beam P6</td>
<td>10 mm to left; 10 mm right</td>
<td>+/- 0 mm</td>
</tr>
<tr>
<td>Beam P7</td>
<td>10 mm to left; 10 mm right</td>
<td>3-4 mm</td>
</tr>
<tr>
<td>Beam P8</td>
<td>10 mm to left; 10 mm right</td>
<td>+/- 0 mm</td>
</tr>
<tr>
<td>Beam P9</td>
<td>10 mm to left; 10 mm right</td>
<td>2-3 mm</td>
</tr>
<tr>
<td>Beam P10</td>
<td>pre-heating off</td>
<td>10-11 mm</td>
</tr>
</tbody>
</table>

Based on the test results (see Tables 3, 4), there is still a need to investigate the capabilities of the horizontal welding line to eliminate pre-heating. The experiences of steel constructions found that if the web size is about 15 mm and the weld size 5–6 mm after I-beams are separated into double T-beams, the T-beams remained straight. When the web is less than 10 mm, although the weld size was small (about 4–5 mm), distortion was noted. The distortion effect was eliminated by pressing the flanges.

The figures below find that the distortion and lateral chamber are difficult to manage because of the large number of parameters. A test without preheating was made after the work, which immediately caused a chamber effect (see beam P10 above).
An additional test used the flange alignment station after the horizontal beam welding line. The alignment station is conventionally used for on beam flange straightening. In the machine, the trapeze nuts located behind the carriages are used to adjust the alignment depth. The aligning rollers are driven to the required dimension, and then the nuts are tightened to this limit. When starting, the alignment dimension should be about the same as the thickness of the flange, or less. The need for alignment depends on the thickness of the flange, height of the flange, size of the weld, material, etc. The alignment must be learnt by the user through experiment. The beam aligning is set so the alignment result can be checked with a right angle or equivalent. If dimension adjustment is needed, the pressing is opened slightly, and the according trapeze nut is adjusted in the necessary direction. The alignment result is then re-checked. The speed is adjusted to low by the speed potentiometer, and the beam drive is pressed. The speed is manually adjusted to a suitable level. The dimensional tolerance requirements are as follows:

- T-beam height +/- 3 mm, plate ≤ 40 mm
- T-beam height +/- 4 mm, plate > 40 mm
- T-beam width +/- 2 mm, plate ≤ 40 mm
- T-beam width +/- 3 mm, plate > 40 mm
- lateral curvature + 0.8 mm/m ; - 0 mm
- camber 1 mm/m
- flange gradient +/- 1 mm

The flange is aligned by the aligning rollers on the drive, and the result is checked. The alignment must be manually stopped by the user before the aligning rollers drop off from the flange. The pressings are opened, and the beam is ready to be taken away from the machine and conveyor. If needed, the aligning procedure may be repeated.

The use of an alignment machine instead of pre-heating showed that when driving the double T-beam through the flange alignment station, pressing the beam flanges but not bending eliminated tension. Bending was not needed after
separating the T-beams into two individual T-beams. When measuring the individual T-beams, the beams were straight, resulting in tolerances of +/- 0 mm.

4.2.2 Testing of the new steel-beam manufacturing process

The manufacture of test beams was made according to the normal fabrication arrangements of “company B” (Fig. 12):

![Image of a welding line with a jig-beam structure](image_url)

**Fig. 12.** Test of a jig-beam structure on a horizontal welding line. A jig is the central web of the guidance beam, but can also refer to the shape or mould of a three-web beam, to which the beam is set in a first step so as to make the rest of the beam in a second step. The central web may also be perforated (see Fig. 11). A jig may also refer to a jig built inside the beam. The central web may serve as the jig, and the jig may accompany the finished beam until its installation. The internal jig may be symmetric or asymmetric.

1. The tests of the steel beam structures manufactured according to WPAR and dimensional tolerance requirements
2. In preliminary cleaning, plates are blast-cleaned from any mill scale or rust before they can be used in the workshop process
3. After the preliminary cleaning, the plates are cut into strips, for webs and flanges. Oxygen/propane, plasma or laser cutting is used as a thermal cutting procedure.

4. Welding
   4.1 Methods
   Welding processes use the welding line, where during the welding, the rolls and rollers press the web and the flanges against each other. On the horizontal welding line, both flanges are welded to the web from the same direction at the same time. For the other side, the welding beam is turned 180°, and welds the second side of the beam. On a box beam welding line, the side plates are welded to the upper and lower beam from both sides at the same time.

   4.2 Size of welds.
   The dimensions of welds include the automatized submerged arc welding process, and the possibility to weld a visible fillet of 7 mm in a single pass. Utilisation of the penetration applies only to automatized submerged arc welding.

5. Providing with fittings
   No stiffeners in guidance

6. Fabrication tolerances
   Welding energy: travel speed, voltage, current

7. Protective treatments
   Protective treatment include classification of environments, surface preparation, anti-corrosive painting, galvanizing

8. Inspections
   Inspections regarding dimensioning and shape, inspection of welds, non-destructive testing, visual inspection, magnetic particle inspection, liquid penetrate testing, ultrasonic inspection, radiographic inspection, destructive testing, samples and weld break tests, NDT (non-destructive testing), (RIL 90-1996); Finnish Transport Agency 2014a).
The phases of manufacturing eight welds for the guidance structures are: 1. material stock, 2. shot-blasting of plates, 3. strip and plate cutting, 4. upper and lower flanges welding to the web on welding process no 1, 5. beam turning for second side welding process, 6. ready-made jig beam transfer to the welding process no 2, 7. side plates installation and box structure welding on process, 8. guidance structure assembly and measurement, and 9. steel-beam shot-blasting, painting and driving.

4.2.2.1 The effect of energy input on jig-beam stiffeners

During the preliminary test it could be recognised that extra plates and stiffeners cause lateral curvature in the jig beam (see Fig.13). The results supported using the horizontal welding line in jig-beam manufacturing to minimise the distortion problem. The test performed that used stiffeners in the jig beam showed that it is necessary to eliminate their use (see Table 5).

Fig. 13. Test of the HSDA beam structure
Table 5. Test results of HSDA jig-beam flange straightness before and after welding. Permitted deviation L/1000 or 6 mm, whichever value is greater (the Finnish Constructional Steelwork Association 2001) L= 6000 mm.

<table>
<thead>
<tr>
<th>Jig beam</th>
<th>Flange straightness before welding</th>
<th>Flange straightness after welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>Upper flange</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+/-0…+/-0…</td>
<td>+/-0…+/-0…</td>
</tr>
<tr>
<td></td>
<td>Lower flange</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+/-0…+/-0…</td>
<td>+/-0…+/-0…</td>
</tr>
<tr>
<td>No.2</td>
<td>Upper flange  (stiffeners)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+/-0…+/-0…</td>
<td>+/-0…+/-0…</td>
</tr>
<tr>
<td></td>
<td>Lower flange</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+/-0…+4…...</td>
<td>+/-0…+/-0…</td>
</tr>
</tbody>
</table>

The above rough analysis of the jig beam as part of the steel-beam structure shows the importance of minimising the welding points of the design. Instead it is better to use the jig beam’s strength capability in the direction of the y-y axis to support the steel-beam structure. Moreover, the steel beam supports the guidance beam’s cost-saving capability in use in a steel-beam railway bridge and HSRs. Three steel-beam variations (in section 4.1) support the continuous steel-beam bridge for modern railway construction.

The effect of the jig-beam tolerances with or without stiffeners is recognised. Extra welding energy causes a distortion effect.
4.2.2.2 Testing the energy input on the HSDA beam

This research had the aim of developing new steel-beam structures to compete with classical foundations, and present a new manufacturing method for large steel beams.

This study is based on the fact that the heat input used in manufacturing the beam is controlled and monitored centrally. The manufacturing tolerances are achieved by the manufacturing method. The measurement of the effect of energy input on two HSDA beam structures – one with stiffeners and another without stiffeners – is as follows (see Tables 6, 7):

Table 6. Test of the effect of extra energy input on the tolerances of HSDA beams

<table>
<thead>
<tr>
<th>Beam height 500 mm</th>
<th>Nozzle 1</th>
<th>640 (A) 32.0 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower flange width 700 mm</td>
<td>Nozzle 2</td>
<td>620 (A) 32.0 (V)</td>
</tr>
<tr>
<td>Lower flange thickness 20 mm</td>
<td>Nozzle 3</td>
<td>550 (A) 27.0 (V)</td>
</tr>
<tr>
<td>Upper flange width 295 mm</td>
<td>Nozzle 4</td>
<td>550 (A) 28.0 (V)</td>
</tr>
<tr>
<td>Upper flange thickness 30 mm</td>
<td>Speed 700 mm/min</td>
<td></td>
</tr>
<tr>
<td>Middle web thickness 15 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side webs 12 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α 80 °</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L = 6000 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The geometric characteristics of the test beams are based on the scaled ratio B/H, where B is the width of upper level flange and H is the height (FWG Magnetschnellbahn Fahrweggesellschaft mbH, 1998 c). Maglev guidance ratio is 2800 mm/2000 mm = 1.4 and the test beam ratio is the same: 700 mm/500 mm = 1.4. Plate thicknesses are the same (Table 6).
Table 7. HSDA beam tolerances before and after welding of side plates. Permitted deviation $D_1-D_2$ with $D_1>D_2$ or $(D_1-D_2)/400$ or 5 mm, whichever value is greater (the Finnish Constructional Steelwork Association 2001).

<table>
<thead>
<tr>
<th>HSDA Beam</th>
<th>Cross-measure between nominally similar diagonal distances $D_1,D_2$ before welding</th>
<th>Cross-measure between nominally similar diagonal distances $D_2,D_2$ after welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In direction A-A</td>
<td>$D_1$ 705 mm 704 mm</td>
<td>$D_2$ 706 mm 705 mm</td>
</tr>
<tr>
<td>In direction B-B</td>
<td>$D_1$ 706 mm 705 mm</td>
<td>$D_2$ 705 mm 705 mm</td>
</tr>
<tr>
<td>No.2 (stiffeners)</td>
<td>In direction A-A</td>
<td>$D_1$ 707 mm 708 mm</td>
</tr>
<tr>
<td>In direction B-B</td>
<td>$D_1$ 706 mm 706 mm</td>
<td>$D_2$ 706 mm 706 mm</td>
</tr>
</tbody>
</table>

Extra welding energy input causes distortion to the HSDA structure and demonstrates the importance of controlling energy input in manufacturing jig beams and guidance steel beam structures.

Based on the measurements above, it could be concluded the jig beam importance as part of a factor in the beam structure. Further to this, the steel-beam guidance with jig beam needs to be manufactured in two processes. Moreover, the potentials of the jig beam are to manufacture it in up/down geometry and/or in left/right geometry of one guideway including other parts of structures. Regarding the manufacturing processes above, the capacity for
producing steel beams per day, week, month, year, etc., can be calculated reliably in accordance with the process time of the manufacturing process carried out in factory conditions.

4.3 Mechanical performance of the selected beam profile compared to I- and box-beams

To test beam profile strength to design the guidance steel beam performance, I-beam and box-beam profile's strength was tested as follows:

1. Beam profile is working linear to buckling of angle webs and/or flange overhang.
2. If the angled web plates and flange overhang stop working, still loading could be increased, because the web in the middle can take more last.

In this work, it was impossible to know what would happen before testing, because the web in the middle can take more last and then prevent the beam breaking, but also prevent buckling of the angle webs.

3. If profile reach the yield strength of pressed edge, then after start plasticizing the cross-section until the web in the middle also loses its load-carrying capacity.

4.3.1 Theoretical profile bending moment

The resistance of the profile subject to the bending moment in this work and the general design criterion for a member subject to bending moment is (the Finnish Constructional Steelwork Association, 2001):
\[ M_{Sd} \leq M_{c.Rd} \]  \hspace{2cm} (2)

where \( M_{Sd} \) is the design value of the bending moment and \( M_{c.Rd} \) is the design moment resistance of the cross-section.

The design moment resistance of a cross-section is calculated in various design values of the cross-section classes as follows (class 1, 2 or 3 cross-sections):

\[ M_{c.Rd} = M_{pl.Rd} = W_{pl}f_y/\gamma_{Mo} \]  \hspace{2cm} (3)

for cross-section classes 1 and 2,

where \( M_{pl.Rd} \) is the plastic bending moment, \( W_{pl} \) is the plastic section modulus of the cross-section, \( f_y \) is the nominal characteristic value of yield strength (355 N/mm\(^2\)), and \( \gamma_{Mo} \) is the partial safety factor 1.1.

Profile
\[ M_{c.Rd} = M_{el.Rd} = W_{el}f_y/\gamma_{Mo} \]  \hspace{2cm} (4)

for cross-section class 3,

where \( M_{el.Rd} \) is the elastic bending moment, \( W_{el} \) is the elastic section modulus of the cross-section, \( f_y \) is the nominal characteristic value of yield strength, and \( \gamma_{Mo} \) is the partial safety factor.

Profile,
\[ M_{c.Rd} = M_{eff.Rd} = W_{eff}f_y/\gamma_{M1} \]  \hspace{2cm} (5)

for cross-section class 4
where $M_{\text{eff, Rd}}$ is the effective bending moment, $W_{\text{eff}}$ is the effective section modulus of the cross-section, $f_y$ is the nominal characteristic value of yield strength, and $\gamma_{M1}$ is the partial safety factor.

In this work $M_{\text{eff}}$ can be reached,

$$M_{\text{eff}} = F \ a$$  \hspace{1cm} (6)

where, $a = \text{distance of forces F symmetrical from the beam heads}$

Then it is possible to calculate the bending force $F$ for beam $M_{\text{eff}},$

$$F = \frac{M_{\text{eff}}}{a}$$  \hspace{1cm} (7)

Beam pressing is started by pressing a beam at $\frac{1}{4}$ points of the beam length at the beginning using force $F,$ and then checking carefully for possible buckling. Subsequently more force $F$ is used, checking for possible elastic moduli, possible plastic deformations, and also the risk of the beam breaking.

Neutral axis of beam structure development,

$$\sum A_i \eta_i = 0,$$  \hspace{1cm} (8)

where $A_i = \text{cross-sectional area of part } I,$ $\eta_i = \text{distance of neutral axis}.$

Knowing values of $\eta_i$ elastic moment of inertia $I_{el}$ can generate the following calculation:

$$I_{el} = \sum \frac{b_i h_i^3}{12} + \sum A_i \eta_i^2,$$  \hspace{1cm} (9)

where $b_i = \text{width of plates}$ and $h_i = \text{height of plates}.$

(see section 3.3.2).
4.3.2 Beam structure development

Experience of manufacturing methods for welded beams was used to develop the first experimental HSDA beam structure in this work. During the development process there was extensive technological need to find a familiar solution. It was important to make the structures, test the new steel-beam structures (strength/weakness analyse), test cross-section buckles and test the greatest compression stress in elements. It was also important to reach the value of the yield strength to develop a new manufacturing system which resulted in new processes. Two separate manufacturing ideas arose: process 1 to make jig beams and process 2 to make the beam structure. This work tested manufactured I-beam and box-beam cross-sectional properties. Cross-sections are classified into four classes, and the same structure may have plates in different classes such as flanges and webs (see the Finnish Constructional Steelwork Association, 2001).

4.3.2.1 Test of I-beam second moment area

The bending of beams test focused on a beam’s co-ordinate system of members of its weak axle (weakness tests performed from the perspective of present products), (see Table 8).

| Flange width 300 mm | Second moment of area Iy = 36364.7 cm$^4$ |
| Web thickness 10 mm  | Second moment of area Iz = 7202.9 cm$^4$ |
| Flange thickness 16 mm | Steel quality fy = 355 N/mm$^2$ |
| Beam height 385.0 mm | Profile length L = 6000 mm |
| Beam weight 103.1 kg/m | Force F allowed for profile bending (axis y-y) $F \geq 447.1$ kN |
|                       | Force F allowed for profile bending (axis z-z) $F \geq 113.6$ kN |
Usually, the seam, shape of the profile, location of the fittings and thicknesses of the paint coating were inspected in the workshop. There was non-destructive testing and destructive testing. Destructive testing was mainly applied in welding and procedural tests and did not actually belong to the daily inspection activity in the workshop. Empirical test rules of steel-beam bridges were used in the design of steel-beam guidance. The only way to analyse the structural strength of a steel beam was via a comparative test of profile load capacity. In the loading the beams tested with a capacity of 2 x 471 kN forces from the point of view of destructive testing. The bending force resulted in scrap in the direction of the I-beam’s weakness, the z-z axis (see Table 9).

Table 9. Observations of the welded I-beam structure’s weakness in the direction of the z-z axis and flange plates of the class 3 cross-section breaking point (see Fig. 5).

<table>
<thead>
<tr>
<th>Edge distance (m)</th>
<th>Sag of span (mm)</th>
<th>Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>used 471 per cylinder</td>
</tr>
<tr>
<td>3.0</td>
<td>breaking/class 3</td>
<td>used 471 per cylinder</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

In this work, the scrap / force capacity was 2 x 471 kN when the I-beam was tested in its weak direction.

An I-beam in the horizontal position bends very easily to the maximum measurement allowed of the bending equipment, creating an S-form and scrap profile (RIL 179, 1989). This method tested the strength usefulness of the I-profile in the z-z axis position, whose capacity is important against snaking caused by trains. It could be recognised that the I-beam structure is weak in the z-z axis by reference to visual inspection (the Finnish Constructional Steelwork Association, 2001).
4.3.2.2 Test of box-beam second moment area

The test was conducted in this work using a rectangular box-beam. For the test, 78 unit box-beams were made available in varying sizes. Box-beam heights varied from 240 mm to 600 mm, the lower flange widths from 300 mm to 600 mm and the lengths from 2,640 mm to 10,800 mm. The total weight of the testing material was 100 tonnes. In the material, the point of interest was the lower flange width made by the box-beam welding line. This method tested box-beam strengths in the vertical position, bending them in the y-y axis using constant pressing (see Table 10).

Table 10. Box-beam cross-sectional properties in test (see Fig. 6).

<table>
<thead>
<tr>
<th>Box-beam height 260 mm</th>
<th>Area of cross-section A = 149.8 cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower flange width 235 mm</td>
<td>Second moment of area Iy = 19218.0 cm⁴</td>
</tr>
<tr>
<td>Lower flange thickness 15 mm</td>
<td>Second moment of area Iz = 26257.6 cm⁴</td>
</tr>
<tr>
<td>Upper flange width 450 mm</td>
<td>Steel quality fy = 355N/mm²</td>
</tr>
<tr>
<td>Upper flange thickness 15 mm</td>
<td>Profile length L = 5,700 mm</td>
</tr>
<tr>
<td>Web thickness 5 mm</td>
<td></td>
</tr>
<tr>
<td>Weight 117.6 kg/m</td>
<td>Force F allowed for profile 5,700 mm bending F≥ 322.4 kN</td>
</tr>
</tbody>
</table>

This work observed box-beam capacity and when box-beams were pressed totally to scrap metal. In the test it could be recognised that the web plate fully buckled to scrap (see the Finnish Constructional Steelwork Association, 2001: SFS-EN 970), but the submerged arc welding was found to be unbroken. The bending force resulted in scrap in the direction of the box-beam’s weakness, the y-y axis (see Table 11).
Table 11. Observations of the welded box-beam structure’s weakness in the direction of the y-y axis and web plate of class 4 cross-section buckling (see Fig. 6).

<table>
<thead>
<tr>
<th>Edge distance (m)</th>
<th>Sag of span (mm)</th>
<th>Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td></td>
<td>max 628/cylinder</td>
</tr>
<tr>
<td>2.85</td>
<td>buckling /class 4</td>
<td>max 628/cylinder</td>
</tr>
<tr>
<td>4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.7</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The above test used a box-beam length of 5.7 m to make observations with a maximum use of force 2 x 628 kN. The result showed that the bending force 2 x 322.4 kN was too strong for the box-beam type, meaning the box-beam structure had weakness in the y-y axis which resulted in the plates buckling.

4.3.2.3 Test of HSDA beam second moment area

Referring to the I-beam and box-beam strength tests above, it could be recognised that the I-beam strength in the second moment of area $I_y = 36364.7$ cm$^4$ and the box-beam strength in the second moment of area, $I_z = 24701.8$ cm$^4$. Observations of the I-beam and box-beam structures supported the technology used in the choice of manufacturing method. The robot system where the product is in place is not useful (see Fig. 14). This was also the case when simultaneously creating the new guidance steel beam structure. The selection included steel plates for webs as well as for upper and lower flanges.

An important result was the need for at least two manufacturing processes instead of one. More processes are needed due to the guidance strength capacity, and they are integrated into the factory layout. Eight welds join the new steel-beam guidance or HSR guidance steel plates to the new steel beam structures.
Higher lateral stiffness can reduce the snaking of a train. The design of the new steel-beam bridge represents a possibility and is necessary to the application of long-distance maglev and high speed lines. The new structure’s high horizontal strength response caused by trains (including high-speed models) could be calculated linearly by using the geometric characteristics of the test beams. Adaptation of the classical foundation is unknown.

Additionally, experience proved very important in creating a steel-beam structure. The structure was created as based on existing I-beam and box-beam weaknesses. Without development, given the weaknesses of I-beam and box-beam test results, the steel-beam guidance problem would have remain unsolved.

In this work, the development and technology solved the classical railway foundation problem. When the steel beam could be recognised technically, the company used its internal stability of experience whilst creating an organisational climate conducive to development. This resulted in adjustments to external change to meet the basic technical requirements for a steel-beam bridge and for HSRs.

**Fig. 14.** Example of product HSDA – H x d1/α/d2 – t1 x B1/t2 x B2 – L calculation

Resulting cross-sectional properties:

- A = area of cross-section (m²)
- g = weight (kg/m)
- Iy = moment of inertia in y-y axis (cm⁴)
- Iz = moment of inertia in z-z axis (cm⁴)
- Wy1 = upper surface major axis section modulus (cm³)
- Wy2 = lower surface major axis section modulus (cm³)
- Sy1 = static moment of upper flange area (cm³)
- Sy2 = static moment of lower flange area (cm³)
In the test above, the data was formed to show the strength of the beam structure as follows (Table 12).

**Table 12.** HSDA beam’s cross-sectional properties (see Fig. 13).

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam height</td>
<td>500 mm</td>
</tr>
<tr>
<td>Area of cross-section</td>
<td>$A = 412.9 \text{ cm}^2$</td>
</tr>
<tr>
<td>Lower flange width</td>
<td>700 mm</td>
</tr>
<tr>
<td>Second moment of area $I_y$</td>
<td>$160064.2 \text{ cm}^4$</td>
</tr>
<tr>
<td>Lower flange thickness</td>
<td>20 mm</td>
</tr>
<tr>
<td>Steel quality $f_y$</td>
<td>$355 \text{ N/mm}^2$</td>
</tr>
<tr>
<td>Upper flange width</td>
<td>295 mm</td>
</tr>
<tr>
<td>Second moment of area $I_z$</td>
<td>$108503.3 \text{ cm}^4$</td>
</tr>
<tr>
<td>Upper flange thickness</td>
<td>30 mm</td>
</tr>
<tr>
<td>Profile length $L$</td>
<td>6000 mm</td>
</tr>
<tr>
<td>Middle web thickness</td>
<td>15 mm</td>
</tr>
<tr>
<td>Angle $\alpha$</td>
<td>80 °</td>
</tr>
<tr>
<td>Profile length $L$</td>
<td>6000 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>324.1 kg/m</td>
</tr>
<tr>
<td>Force $F$ per cylinder</td>
<td>$\geq 1357.5 \text{ kN}$</td>
</tr>
</tbody>
</table>

The first step in the testing was to determine the purpose and objectives of the test and evaluate the overall quality and expected level of performance. The results showed that the first beam structures were designed with strength in accordance with their bending capability (see alpha test Rainey, 2008). According to the strength/weakness test of the above profiles and analysis, the angle side plates-based classification of the cross-section class is 1, but in middle class web class 2, however, the last side web plates bent without buckling. This was an important finding with regard to the jig-beam value. The test proved correct. No significant bending data was found (1 mm) when testing the new steel-beam strength using the same 2x 628 kN of pressing force. A bigger hydraulic cylinder would be required if further bending were to be undertaken (Table 13).
Table 13. Observations of the HSDA beam structure strength in the direction of the z-z and y-y axis without buckling (see Fig. 13). Max bending allowed in railways L/600 (RIL 90-1996).

<table>
<thead>
<tr>
<th>Edge distance (m)</th>
<th>Sag of span (mm)</th>
<th>Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>max 628 used/cylinder</td>
</tr>
<tr>
<td>3.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td>max 628 used/cylinder</td>
</tr>
<tr>
<td>6.0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The geometric characteristics in the test were based on ratio B/H, where beam height is 500 mm and the lower level flange is 700 mm. The maximum possible force was $2 \times 628 \text{ kN} = 1256 \text{ kN}$. The force was less than required for the allowed bending calculated as $2 \times 1357.5 \text{ kN}$ (see Table 15). The capacity of the cylinder was too small.

The new steel-beam structure and bending test data was important for calculations of larger geometric characteristics. The first results proved the strength capacity of the profile in the directions of the y-y and z-z axes, in spite of the beam structure weight, was small.

When comparing HSDA structure to the same height of hot-rolled profile HE 500 M (European Wide Flange Beams 2018), the $I_z$ capacity of the profile is 19,155 cm$^4$. That is 82% less than the same height of HSDA. The $I_y$ values are about the same.

In this work, smaller and bigger HSDA steel-beam structures are integrated with the manufacturing method capacity. The reproduction tests are in section 4.4.1.
### 4.3.3 Selecting beam strength

As described above in the first step for the first part of the beam, an H-beam or I-beam may be assembled to form the jig beam. In the second step, side plates are added to this beam.

At the first welding station, the entire middle web may be welded on both sides; and after the straightener, at the second welding station, the side seams may be welded to the H-beam.

After both sides have been run on the second machine, the steel beam has eight seams. Alternatively, the steel beam may have a different number of seams, for instance six, ten, or twelve. The potentials in designing the beam structures are:

1. possibilities to calculate steel-beam guidance strength for parameters in the co-ordinate system of members
2. plates to be welded must press against each other during welding,
3. steel-beam structures have high torsional stiffness,
4. the horizontal strength structure of side plates needs to be considered,
5. either no or minimised stiffeners because of automated manufacturing,
6. welding of plates using a longitudinal submerged arc,
7. beam structure, side plates can be at an angle or in a vertical position, and
8. scaled beam tests are useful when developing manufacturing methods for larger maglev guidance or HSR steel beam and their production

In designing of fatigue-loaded structures, increasing the cross-section reduces the stress range but increases the weight of the structure. In tests, we eliminated vertical and horizontal stiffeners welded to the jig beam and to the flange plate, and used the jig beam in the total beam structure. In that way we minimize and constrained on stress, deflection and stability. Rejecting stiffeners, new manufacturing method allow different sizes of beams to allow to consider cost-saving function.
Enclosed examples of the steel-beam HSDA and HSDQ structures:

Table 14. Calculation of HSDA's parameters and strengths in the directions of the z-z and y-y axes (Eurocode EN 1993-1-1 Eurocode 3) (see Fig. 20).

HSDA 573 x 12 / 77 / 8 - 18 x 640 / 40 x 252-6000 (Input data).

Dimensions (raw data):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>573.0 mm</td>
</tr>
<tr>
<td>d1</td>
<td>12.0 mm</td>
</tr>
<tr>
<td>d2</td>
<td>8.0 mm</td>
</tr>
<tr>
<td>α</td>
<td>77.0°</td>
</tr>
<tr>
<td>B1</td>
<td>640.0 mm</td>
</tr>
<tr>
<td>B2</td>
<td>252.0 mm</td>
</tr>
<tr>
<td>t1</td>
<td>18.0 mm</td>
</tr>
<tr>
<td>t2</td>
<td>40.0 mm</td>
</tr>
<tr>
<td>L</td>
<td>6000.0 mm</td>
</tr>
</tbody>
</table>

Cross-sectional properties (See Section 3.3.2):

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>416.0 cm²</td>
</tr>
<tr>
<td>g</td>
<td>327.0 kg/m</td>
</tr>
<tr>
<td>Iy</td>
<td>21,771.9 cm⁴</td>
</tr>
<tr>
<td>Iz</td>
<td>108,310.2 cm⁴</td>
</tr>
<tr>
<td>Wy1</td>
<td>6,994.6 cm³</td>
</tr>
<tr>
<td>Wy2</td>
<td>8,317.8 cm³</td>
</tr>
<tr>
<td>Sy1</td>
<td>3,219.0 cm³</td>
</tr>
<tr>
<td>Sy2</td>
<td>2,911.6 cm³</td>
</tr>
</tbody>
</table>

Force F per cylinder needed for bending ≥ 1,655.4 kN
Table 15. Calculation of HSDQ’s parameters and strengths in the directions of the z-z and y-y axes (Eurocode EN 1993-1-1 Eurocode 3), (see Fig. 22).

HSDQ 573 x 12 / 8 - 18 x 640 / 40 x 512 – 6,000 (Input data).

Dimensions (raw data):

\[
\begin{align*}
H &= \text{total height of the web } 573.0 \text{ mm} \\
d_1 &= \text{thickness of the edge plate } 12.0 \text{ mm} \\
d_2 &= \text{thickness of the middle plate } 8.0 \text{ mm} \\
B_1 &= \text{width of the top flange } 640.0 \text{ mm} \\
B_2 &= \text{width of the bottom flange } 512 \text{ mm} \\
t_1 &= \text{thickness of the top flange } 18.0 \text{ mm} \\
t_2 &= \text{thickness of the bottom flange } 40.0 \text{ mm} \\
L &= \text{length of beam } 6000.0 \text{ mm} \\
\end{align*}
\]

Cross-sectional properties (See Section 3.3.2):

\[
\begin{align*}
A &= \text{area of cross-section } 517.0 \text{ cm}^2 \\
g &= \text{weight } 405.8 \text{ kg/m} \\
I_y &= \text{moment of inertia in axis y-y } 28,787.38 \text{ cm}^4 \\
I_z &= \text{moment of inertia in axis z-z } 18,4529.0 \text{ cm}^4 \\
W_{y1} &= \text{upper surface major axis section modulus } 11,326.5 \text{ cm}^3 \\
W_{y2} &= \text{lower surface major axis section modulus } 9,028.8 \text{ cm}^3 \\
S_{y1} &= \text{static moment of upper flange area } 4,987.6 \text{ cm}^3 \\
S_{y2} &= \text{static moment of lower flange area } 3,569.4 \text{ cm}^3 \\
\end{align*}
\]

Force F per cylinder needed for bending ≥ 2,136.8 kN

The calculations for HSDA (See Table 14) showed a need for a minimum bending force of 1655.4 kN and for HSDQ (See Table 15) a minimum bending force of 2,136.8 kN. Calculating the difference between the bending forces resulted in a 481.4 kN better bending capacity for HSDQ.
When comparing the difference of structures as horizontal swing absorber, the beam upper level flanges are the same width. Results showed the HSDA structure $I_z$-value was 108,310.2 cm$^4$ and the HSDQ $I_z$-value 184,529.0 cm$^4$. The calculation of the difference resulted in HSDQ having a 76,218.8 cm$^4$ higher moment of inertia.

When compared to the above $I_z$-value of HSDK, the beam structure results in an $I_z$ value of 23,3554.9 cm$^4$: its higher level has the HSDQ $I_z$-value.

Further to the parameters above, there no moment of inertia value for embankment structures is available. There are displacement investigations in lateral directions (Zand & Moraal, 1997) and conventional track structure and principles of load transfer (Esveld 2017). Literature on classical railways, maglev- and high-speed rails does not present guidance and the manufacturing method of the steel-based track foundation (see Fig. 15, 16, 17, 18):
Fig. 15. Comparison of bending force needed for buckling, H-beam in Tables 11, 12; box beam in Tables 13, 14; HSDA 1 beam strength capacities HSDA 1 in Tables 15, 16; HSDA 2 beam in Table 17, HSDQ beam in Table 18.

Fig. 16. HSDA guidance beam strength potential to increase $I_z$-value.
**Fig. 17.** HSDQ guidance beam strength potential to increase $I_y$ value.

**Fig. 18.** HSDA guidance beam $I_y$ and $I_z$ potentials for steel-beam bridges.
4.4 Energy input measurement during welding

Based on the strength/weakness tests above, the steel-beam structure forms a new strength with the angled webs or the webs are at right angles. In terms of cross-sectional properties, the moment of inertia is in the direction of the y-y axis and z-z axis.

The steel beam presented new structures and advantages to eliminate vibration of guidance or rails as caused by trains. The strength calculations of the steel beams are programmed in this work to calculate the strength of a steel beam in every millimetre of the steel beam sizes. Energy input control was developed for steel-beam manufacturing processes from start to end.

The preliminary test (see section 4.2.1) of energy input focused on data from the existing manufacturing process. The weakness test was used to obtain results for the beam weak axle (Fig. 5.6). The strength/weakness test was used when manufacturing jig beams for the beam structure. The importance of the two manufacturing processes, recognised in the steel-beam structure, resulted in the steel beam for the railway bridge.

4.4.1 Test reproduction

Based on the tests of distortion and bending unit power requirements, there was a need to control the energy input data in welding systematically, in order to keep the beam structure within its tolerances.

This test used automated welding heads. The electrical control system maintains the pre-set current and voltage. In the reproduction tests the welding head was stationary and the beam moved. The parameters are based on experiments in factories (see sections 4.2.1 and 4.2.2).

The ideal welding procedure will produce acceptance quality welds at the lowest over-all cost. Many factors influence the optimum welding conditions. In selecting a procedure, the best approach is to study the conditions of the
application and then choose the procedure that is closest to nearly accommodating them (Lincoln Electric (1973)).

Chandel & Bala (1985) investigated the cooling time and features of submerged arc weld beds. This can be expressed in terms of fusion area, HAZ area (Heat Affected Area) and HAZ boundary length. They found that as the heat input increases, the time required to cool the weld between 800–500°C also increases. Some of the significant scatter in results were probably due to the welding techniques, including current, voltage, polarity, travel speed, electrode extension, electrode diameter and V-groove, which influenced the cooling time. Weld features were measured such as bead-on-plate welds and V-groove welds to the horizontal flat plates.

Gunaraj et al. (2002) found that heat input – calculated using welding current, welding voltage and welding speed – exerted considerable positive impact on almost all HAZ dimensions of structural steel pipes.

Poorhaydari et al. (2005) observed the microstructural changes in the weld zone, as well as the weld heat-affected zone HAZ. These are greatly dependent on the heating and cooling rates. In turn, this depends on the weld heat input, the plate thickness/geometry, and the initial pass temperature. The researchers note that more work is needed for application to plates with other geometrics/positions and an examination of a wider range of welding variables. An investigation was made into horizontal welding, using small flat plates 285 mm x 165 mm in sizes.

Results support the importance of an energy input control system. In reproduction tests for removing shrinkage forces by stress relief, the energy input was to an elevated temperature, and was followed by controlled cooling.

Enclosed tests use a SAW welding method in three welding lines to create two manufacturing processes. The first process is for manufacturing jig beams; the second is to manufacture the HSDA and HSDQ structure (Tables 16, 17, 18, 19).
Table 16. HSDA jig-beam design and observed energy input parameters.

Reproduction test (see Fig. 19):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nozzle 1a</th>
<th>689 (A) 27.2 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam height 573 mm</td>
<td>Nozzle 1b</td>
<td>685 (A) 27.5 (V)</td>
</tr>
<tr>
<td>Lower flange width 252 mm</td>
<td>Nozzle 2a</td>
<td>693 (A) 26.8 (V)</td>
</tr>
<tr>
<td>Lower flange thickness 40 mm</td>
<td>Nozzle 2b</td>
<td>672 (A) 26.8 (V)</td>
</tr>
<tr>
<td>Upper flange width 640 mm</td>
<td>Speed a</td>
<td>580 mm/min (side a)</td>
</tr>
<tr>
<td>Upper flange thickness 18 mm</td>
<td>Speed b</td>
<td>655 mm/min (side b)</td>
</tr>
<tr>
<td>Middle wed thickness 8 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L=6000 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 19. The HSDA jig-beam welding line test. Technical specification: Assembly conveyors Welding Unit 600/Q, Transfer Conveyors.
Table 17. HSDA beam structure design and observed energy input parameters.

Reproduction test (see Fig. 20):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nozzle 1/1</th>
<th>Nozzle 2/1</th>
<th>Nozzle 3/1</th>
<th>Nozzle 4/1</th>
<th>Nozzle 1/2</th>
<th>Nozzle 2/2</th>
<th>Nozzle 3/2</th>
<th>Nozzle 4/2</th>
<th>Nozzle 3/3</th>
<th>Nozzle 4/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam height 573 mm</td>
<td></td>
<td></td>
<td>670 (A) 27.5 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower flange width 252 mm</td>
<td></td>
<td></td>
<td>690 (A) 27.6 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower flange thickness 40 mm</td>
<td></td>
<td></td>
<td>580 (A) 26.8 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper flange width 640 mm</td>
<td></td>
<td></td>
<td></td>
<td>560 (A) 26.9 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper flange thickness 18 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>649 (A) 27.6 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle wed thickness 8 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>658 (A) 27.8 (V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side webs 12 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>578 (A) 26.2 (V)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \alpha = 77^\circ )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>582 (A) 26.4 (V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L = 6,000 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>575 (A) 26.2 (V)</td>
<td></td>
</tr>
<tr>
<td>Speed /500 mm/min (drive 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>576 (A) 26.4 (V)</td>
</tr>
<tr>
<td>Speed /480 mm/min (drive 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 20. The HSDA structure welding line test. Technical specification: Assembly Conveyors, Welding Unit 700/Q and Transfer Conveyors.
Table 18. HSDQ jig-beam design and observed energy input parameters.

Reproduction test (see Fig. 21):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nozzle 1a</th>
<th>Nozzle 1b</th>
<th>Nozzle 2a</th>
<th>Nozzle 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam height 573 mm</td>
<td></td>
<td></td>
<td>596 (A) 28.5 (V)</td>
<td></td>
</tr>
<tr>
<td>Lower flange width 512 mm</td>
<td></td>
<td>Nozzle 1b</td>
<td>612 (A) 29.5 (V)</td>
<td></td>
</tr>
<tr>
<td>Lower flange thickness 40 mm</td>
<td>Nozzle 2a</td>
<td></td>
<td>659 (A) 28.5 (V)</td>
<td></td>
</tr>
<tr>
<td>Upper flange width 640 mm</td>
<td>Nozzle 2b</td>
<td></td>
<td>647 (A) 28.6 (V)</td>
<td></td>
</tr>
<tr>
<td>Upper flange thickness 18 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle web thickness 8 mm</td>
<td>Speed a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L = 6,000mm</td>
<td>Speed b</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Speed a                                |           | 650 mm/min (side a) |
| Speed b                                |           | 660 mm/min (side b) |

Fig. 21. The HSDQ jig-beam welding line test. Technical specification: Assembly Conveyors, Welding Unit 3000 CPS, Transfer Conveyors, Flange Alignment Station with Receiving Conveyors.
Table 19. HSDQ beam structure design and observed energy input parameters.

Reproduction test (see Fig. 22):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nozzle 1/1</th>
<th>Nozzle 2/1</th>
<th>Nozzle 3/1</th>
<th>Nozzle 4/1</th>
<th>Nozzle 1/2</th>
<th>Nozzle 2/2</th>
<th>Nozzle 3/2</th>
<th>Nozzle 4/2</th>
<th>Nozzle 1/3</th>
<th>Nozzle 2/3</th>
<th>Nozzle 3/3</th>
<th>Nozzle 4/3</th>
<th>Nozzle 1/4</th>
<th>Nozzle 2/4</th>
<th>Speed /1</th>
<th>Speed /2</th>
<th>Speed /3</th>
<th>Speed /4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam height 573 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>545 (A) 26.6 (V)</td>
<td>545 (A) 26.4 (V)</td>
<td>530 (A) 25.6 (V)</td>
<td>545 (A) 25.4 (V)</td>
<td></td>
</tr>
<tr>
<td>Lower flange width 512 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>640 (A) 27.4 (V)</td>
<td>615 (A) 27.6 (V)</td>
<td>625 (A) 27.2 (V)</td>
<td>620 (A) 27.4 (V)</td>
<td></td>
</tr>
<tr>
<td>Lower flange thickness 40 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>625 (A) 27.7 (V)</td>
<td>625 (A) 27.6 (V)</td>
<td>625 (A) 27.7 (V)</td>
<td>625 (A) 27.6 (V)</td>
<td></td>
</tr>
<tr>
<td>Upper flange width 640 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>620 (A) 27.4 (V)</td>
<td>630 (A) 27.6 (V)</td>
<td>625 (A) 27.7 (V)</td>
<td>625 (A) 27.6 (V)</td>
<td></td>
</tr>
<tr>
<td>Upper flange thickness 18 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>525 (A) 26.0 (V)</td>
<td>525 (A) 25.2 (V)</td>
<td>525 (A) 26.0 (V)</td>
<td>525 (A) 25.2 (V)</td>
<td></td>
</tr>
<tr>
<td>Middle wed thickness 8 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600 (A) 27.7 (V)</td>
<td>593 (A) 27.9 (V)</td>
<td>600 (A) 27.7 (V)</td>
<td>600 (A) 27.7 (V)</td>
<td></td>
</tr>
<tr>
<td>Side webs 12 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>555 mm/min (drive 1)</td>
<td>398 mm/min (drive 2)</td>
<td>420 mm/min (drive 3)</td>
<td>420 mm/min (drive 4)</td>
<td></td>
</tr>
<tr>
<td>L= 6000 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>555 mm/min (drive 1)</td>
<td>398 mm/min (drive 2)</td>
<td>420 mm/min (drive 3)</td>
<td>420 mm/min (drive 4)</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 22. The HSDQ structure welding line test. Technical specification: Assembly Conveyors, Welding Unit 700/Q and Transfer Conveyors.

Results of jig beam straightness (see tolerances in Table 5).

Table 20. HSDA and HSDQ jig-beam flange straightness before and after welding (Fig. 19, 21).

<table>
<thead>
<tr>
<th>Beam</th>
<th>Flange straightness before welding</th>
<th>Flange straightness after welding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HSDA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper flange</td>
<td>+/−0...+/−0...+/−0</td>
<td>+/−0...+/−0...+/−0</td>
</tr>
<tr>
<td>Lower flange</td>
<td>+/−0...+/−0...+/−0</td>
<td>+/−0...+/−0.4...+/−0</td>
</tr>
<tr>
<td><strong>HSDQ</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper flange</td>
<td>+/−0...+/−0...+/−0</td>
<td>+/−0...+/−0...+/−0</td>
</tr>
<tr>
<td>Lower flange</td>
<td>+/−0...+0.5...+/−0</td>
<td>+/−0...+0.5...+/−0</td>
</tr>
</tbody>
</table>
Results of cross-measurement tolerance (see tolerances in Table 7).

### Table 21. HSDA and HSDQ beam tolerances before and after welding of side plates (Fig. 20, 22)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Cross-measure between nominally similar diagonal distances D1,D2 before welding</th>
<th>Cross-measure between nominally similar diagonal distances D2,D2 after welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSDA</td>
<td>In direction A-A</td>
<td>In direction B-B</td>
</tr>
<tr>
<td>D1</td>
<td>722 mm</td>
<td>723 mm</td>
</tr>
<tr>
<td>D2</td>
<td>724 mm</td>
<td>725 mm</td>
</tr>
<tr>
<td>HSDQ</td>
<td>In direction A-A</td>
<td>In direction B-B</td>
</tr>
<tr>
<td>D1</td>
<td>812 mm</td>
<td>812 mm</td>
</tr>
<tr>
<td>D2</td>
<td>812 mm</td>
<td>812 mm</td>
</tr>
</tbody>
</table>

Following start-up, the work cycle for the process of manufacturing a steel beam begins (see section 4.2.2). From storage, the plate parts are transferred to assembly conveyors, where they are assembled by means of pressure rolls to form a beam with a final cross-section. From the assembly conveyors, the beam proceeds to an assembly unit, where the seams of the separate plate parts are joined or brought together. The finished beam is transferred to a transfer
conveyor. Then HSDA and HSDQ tolerances (cross-measures) tests are performed before and after welding (see Fig. 20, 22).

As shown, the jig beam is part of the steel-beam structures. Transrapid’s guidance was designed to use cross stiffeners. The design and assembly of guidance was based on a form of cross stiffeners. Many tack welding points are needed to keep this guidance in shape. Extra welding points cause extra energy input and distortion (see section 3.2.3).

The reproduction test showed differences in cross-measurements caused by the lower flange tolerance of the jig beam (see Table 20). This results in increased importance of a wider jig beam flange tolerance in the manufacturing process. Also, there is a need for careful energy input control. This finding resulted in the reproduction test being undertaken the same way as in the first test (see Table 5).

Based on the first and reproduction tests, the steel-beam structure follows the jig-beam tolerances. If the jig-beam straightness is within the tolerances, the steel-beam structure keeps within the tolerances. The same is also true for steel-beam railway guidance.

The consideration of the energy values input into the seams allows for different changes and curvatures to be compensated for during manufacture with regard to the vertical and/or horizontal curvature effect in the manufacturing of the steel beam. This is made possible by increasing or decreasing the energy input into one or more seams.
4.4.2 The new energy input control system in the manufacturing method

The manufacturing method had new mechanical functions in order to measure energy. Welding control units, welding power supplies, welding wire feeders, welding nozzle motions, hydraulic unit and hydraulically had operating functions. In addition, a flux vacuum system and different electric motors for beam transfer are used for the welding process. The welding line operator has measured data. There was an automation system with a programmable logic controller, control data, and a control panel which a data operator controls. An operator gives the control data for the mechanical welding line functions.

The energy value input to each seam can be measured and adjusted individually. Alternatively, the adjustment may be simultaneous and/or equivalent. It is possible to use the assembly equipment’s energy input synchronisation device or measuring system, which enables measurement to ensure that the same amount of energy is input into each seam. The parts to be joined to the beam are kept straight or at the required straightness or curvature (see Fig. 8).

In the first step of manufacturing a steel beam, the assembly device is arranged to connect the middle web plate of the steel beam to the bottom and top flanges to form a jig beam (see Fig. 19). The connection may take place by supporting or welding the middle web plate. It is at one point to the bottom flange and at one point to the top flange. In the second step the assembly device is arranged to connect the first edge of the jig beam to a first side web plate and second side web plates, and on at least one side to the bottom and top flanges. Welding is done by a welding machine in the assembly device or connected thereto.

The measured value, energy or energy amount may be compared with one or more reference values. Measuring the response to the comparison enables the calculation or otherwise definition a new or subsequent value for the energy amount to be input to the joining point. Measuring the amount of energy input to the joining point and/or used in joining enables the adjustment of the amount.
of energy input to the joining point. The latter value may be the same as or different than the former value.

The energy input measurement is adapted to control the amount of energy input into the seam in all or some of the seams. The equipment is also adapted to keep the energy values exactly the same or substantially the same. According to an alternative implementation, the amount of energy input to the seams can be substantially the same in one entire seam, but be different in value in at least one other entire seam or part thereof. Each steel-beam structure contains a jig beam, and energy input measurements follow the steel beam until the installation. The data can also be considered part of the life-cycle data of the product.

In the manufacturing method of a steel-beam railway bridge, the energy input can be measured at the cross-section of the beam. Measuring as a function of length at regular or irregular intervals at points L1, L2, L3, etc., L represents a measure of length starting from zero and ending where the beam ends (see Fig.23, 24).

Each energy measurement can be registered automated during manufacture, and it is possible to send the data over the Internet, for instance, to the reader, computer, or server, where the data can be stored or processed. The data can be used in planning and dimensioning the cutting data of the plate and other corrective data.

The energy input of a steel-beam structure is measured as a function of length at four points simultaneously. The thermal energy input to the weld is calculated or derived from the measurement. The measured value is compared with a permanent or variable reference number point during the manufacture. The input of thermal energy can also be measured with separate sensors. The assembly equipment may compare a signal received from a sensor with one or more predefined threshold values, but also limit values and/or other measuring values can be set. The energy or power being supplied is adjusted on the basis of the measurement and comparison.

It is possible to control the manufacture of a steel-beam guidance by means of the control value received from the equipment: thus, in accordance with the tolerance requirements of the steel-beam railway bridge and the energy supplied to the seam or the maximum value of heat input. Those maximum values can be
obtained from the material specifications of the beam material supplier for various steel grades (see Fig. 23).

**Fig. 23.** Energy input control system of the jig beam. The assembly apparatus may control and monitor the manufacture of the internal jig. Energy input may be controlled in a centralised and seam-specific manner with energy input synchronisation apparatus or control apparatus. Variations from upper side figure to down side: welding speed (black); current (red); energy input (violet), voltage (blue), in welding points L= 212–2,212 mm
Fig. 24. Energy input control system of the jig-beam. Variations from upper side figure to downside: welding speed; current; energy input, voltage, in welding points $L = 3.135 - 3.935$ mm.

The energy input into the seam measured with a sensor connected to a measuring device, the sensor data fed into the measuring device and to an adjusting device. The readings of the adjusting device and measuring device are sent to the control panel and also set control values for the adjusting device, measuring device, and welding machine (See section 3.4.2).
4.5 Research work

A new energy measurement system in the manufacturing method of steel-beam guidance and applications is introduced to the scientific community. Figs. 23 and 24 show the energy input control system of the jig beam. In the steel-beam manufacturing method, the energy input can be measured at the cross-section of the beam. Measuring as a function of length of any steel beam is not found in the literature. Every input may be controlled in a centralised and seam-specific manner with energy input synchronisation equipment or control equipment. Measurement as a function of the length of any steel beam is not founded in the literature.

The research work was carried out over a relatively long period of time focusing on the planning of Transrapid Berlin-Hamburg from 1994 to 2005. The construction was intended to start in 1999. After that, the work was started in companies A and B. For the construction of the guideway, the author received planned drawings for two types of guidance. The height of the larger guidance was 2000 mm, and the smaller height 1000 mm. After the analysis of this guidance, manufacturing presented problems. In the companies A and B, there was an attempt to find some solution for manufacture, but some ideas had to be rejected. During this phase, some developers in Germany also rejected the Transrapid project.

Vision (Fig.1) could be identified for the solution in the analysis of classical railways as well as high-speed rail situations during the same period. In the future, positive impact will also be needed to develop the operation of regional and freight rails.

Based on the tests in companies A, B, D and E, the idea during the first step of a holed jig beam could be facilitated by the manufacture of a new guidance beam structure. The four welds tested operation using I-beam shapes in various welding lines in accordance with new and older WPS or by trial and error, but also by utilising welding experts from company E. Co-operation with company E was important in the tests on maximum capacity. In two-and-a-half shifts, 1000
In company D, the beam deformations were measured after the welding of the first and second tests, and they have provided satisfactory results. All the values found within the allowable limits were indicated on the applicable specification and standards. The results support the tests undertaken by Company B (in Tables 5 and 20).

The advantage related to the long research period was that there was enough time to gather data as well as time to test and improve the method. The disadvantage was that the research results could not be presented to the international scientific community until late in the research work.

Nevertheless, feedback during the early research phases led the research to new steps of consideration of new steel-beams and manufacturing methods. Most important was to see a new steel-beam structure as the tested holed web creating three-web slant-webbed A-casing. After that finding in rough sensitivity analysis, “what if” was applied to determine which one resulted in a new path and direction for the novel steel-beam structure. The decision for a new path supported more related technology, factors and importance of energy input parameters. The decision was important compared to the problems of Transrapid guidance manufacturing by robot in “Company C”, as well as in classical railway foundations, steel bridges and other applications. Results indicated that the novel steel-beam structure has the greatest impact on the development of alternative plans, such as HSDA and HSDQ guidance beam strength potential, to increase the $I_z$-value and $I_y$-values. (Figs. 16, 17 and 18).

Moreover, the novel steel-beam structure brings out significant new possibilities in terms of cost-savings. Compared to existing methods, technology can be optimised to find a solution that produces the highest cost-savings. For example, differences in direct steel material and direct labour cost, etc., can be calculated as based on the optimisation of a guideway structure having tight strength values. Experiences in the use of a robotic positioning table to fabricate a guidance beam according to drawings of Transrapid do not show the results of the cost-savings in “Company C”.

The ability for “Company A” and “Company B” to manufacture products that meet tight tolerance standards include the first assembly device arranged to weld
the jig beam in the first step. This technology is missing in the scientific community. The second assembly device managed to receive the jig beam and weld the side web plates to the jig beam. The tolerances of the steel-beam structure is monitored in such a manner that energy input in each weld is the same and/or as required.

However, application of the method to other products would need a comprehensive test data process creation to be useful.

The research work consists of the development of the three-web steel-beam structure and manufacturing method. By this means the work can be repeated, and obtain the same results as those presented in this dissertation.
5. DISCUSSION

5.1 The result in the light of a new state-of-the-art energy input control system

Residual stresses in automated manufacturing and the influence on distortion in the de-coiling were analysed. Steel was considered from the point of view of the plate’s spring back during uncoiling. The distortion was focused on the material de-coiling. Researchers came to the conclusion that the distortion during welding is dependent on the de-coiling history. However, the welding was not analysed. (Kazanowski & Misiolek, 2002).

The research on the steel material welding has resulted in further knowledge on welding methods, especially with respect to the optimisation of parameters for polarity in submerged arc welding and furnishing quality welds. It was found to be essential to achieve high quality and cost-effective welds. Researchers used a welder machine (tractor type). Runs were made on the base material to obtain the working parameters. DCEP and DEEN polarity in submerged arc welding was in use. (Singh et al., 2015).

Also, the heat absorbed by plates of two different thicknesses were obtained by cryogenic calorimeter using MIG/MAG welding. Bead on plate welds were performed using steel plates with thicknesses of 3.2 mm and 9.5 mm. In order to make a comparison, varying bead lengths from 10 to 150 mm long for each thickness were used. The welding time was from 3.21 to 28.8 seconds. (Quintino et al., 2013).

The capability of the two-wire submerged arc welding process in a high-deposition welding process was investigated for improving productivity. In this welding method, the leading wire was connected to either DC or AC and the
trailing wire to AC. Researchers found that the arc interaction on molten droplets had a significant impact. The transfer direction was evident and the molten droplets from leading and trailing electrodes followed the axis of the corresponding arcs. This was performed at the time of detachment and reached the weld pool in SAW-T welding when welding conditions used to perform bead-on groove experiments in plates of 780 mm x 360 mm x 17.5 mm. (Kiran et al., 2014) applied.

When evaluating the influence of welding variables on weld beads by the submerged arc process, the researchers used conventional current, aiming the future application in overlays against corrosion. They found that welding was one of the main fabrication processes used in various segments of metal work, and also in the mechanical engineering industry, such as in shipbuilding and boiler-making services. The techniques included changing the type of current, inverting the polarity of current or changing the contact tip work design. The researchers found that in welding it was not possible to adjust the current on the machine to the desired values (Mesquita da Silva et al., 2017).

An investigation of metal transfer in submerged arc welding was made by using high-speed videography technology. The behaviour of the metal transfer in SAW welding was filmed through a stainless steel pipe. The test resulted in three different metal transfer modes. The analysis indicated that the electric arc and short-circuiting bridge may exist simultaneously when the third mode occurs. This is completely different from gas metal arc welding (GMAW). In the groove test, the workpiece was in place, and welding moved on a small plate (Wu et al., 2017).

Analysing active power measurement in arc welding and its role in heat transfer to the plate was investigated. Researchers support the importance of energy input, which is produced by the electric arc and transferred onto/into a plate. The heat input is extremely important, not only for bead geometric formation but also for metallurgical transformations. These influence the mechanical properties of the joints in GTAW in constant and pulsed current and GMAW short-circuiting with different inductance settings (Jorge et al., 2017).

However, the continuous steel-beam bridge in the railway industry has not yet been studied. This study offers a cost-effective solution focusing on steel-beam railway bridges.
5.2 Evaluation of the research

When starting the development work, observations could be made with respect to resulting errors by business contact (Table 1). For example, the main beams were of exceptional quality and 48 main beams per day were used at maximum capacity. Wavy webs – the wave in the web creates enormous fit-up and assembly problems. Rolled flanges and flanges were not perpendicular to the web. The rolled flanges required a great deal of rework on the assembly line as associates attempted to level the flanges to an acceptable level. In the case of bowed beams, longitudinal and curved in appearance along the beam, these require rework to straighten, increasing the cost of the beam. Incorrect camber beams that do not have enough camber or sets of beams that do not have a matching camber require heating in order to fix camber. All welds were fillet welds on both sides of the beam, using sub-arc welding, etc. Welding parameters DC Volts 28/32, DC Amps 400/475. The process was a pull-through welding system, which utilises twin-electrode, submerged arc welding.

The evaluation of I-beam manufacturing with two machine units was critical when the welding speed was higher than 1.5 metre/min in “Company D”. The laser guiding system for torches has been removed due to poor functioning. Also, the ground links do not guarantee the continuity of the contact due to evident insufficient designing valuation. In general, the analysis made on the horizontal welding line was complete for lighter and holed test beams.

Evaluation of I-beam manufacturing with one welding unit by “Company E” used welding speed parameters of 120 cm/min, 190 cm/min and 230 cm/min. Their vertical T-beam welding line was about 30 years old. The machine was for piece-by-piece production (not intended for continuous production). The other machine does not offer capabilities for modern shipbuilding. The importance of the need of new lines to manufacture several web pairs of one plate by optimising the steel plate for transferring to modern welding line was emphasised. Company E had very tight tolerances in measuring energy input. Accordingly, the WPS weld size was 2.6 mm ± 0.4, energy input < 5 kJ/cm; weld size 3.5 mm ± 0.5, energy input < 8 kJ/cm, weld size 5.5 mm ± 0.5, and energy input <10 kJ/cm. Those parameters were important in designing a new process for company E.
High-quality steel was used in ship building. The problems were the same as in Company D when used at higher speed: in that case, steel material needed to be shot-blasted. In Company E, this process was underestimated. Even a small foot track caused holes in the weld, affecting quality, and this includes anticipated risks at higher welding speeds. When using a lower welding speed (120 cm/min), the problem disappeared.

The tests supported the conclusion that the lines in Companies D and E need novel energy input control suitable for the modern steel-beam manufacturing process in shipyards. In this work that resulted data for holed and not holed jig-beam manufacturing. This work resulted in data for holed and not-holed jig-beam manufacturing.

The new technology applies a new steel-beam structure and new manufacturing method combined with energy input control system. Evaluating the objectivity of research, testing is based on operation instructions in the companies A and B. The same regarding Companies C, D and E. Strength calculation program delivered by outside technical research company. Manufacturing construction made by workers in the company A and method testing made by operators in the company B. according operation instructions, work planning, designs testing works in details. In welding lines developed according guidance steel-beam manufacturing at first, start inspection of the required material for the operation phase by using the work instruction. Measures of the guidance steel-beam are checked. The process adjusted by operator to the proper beam size. Welding performed in accordance with instruction. The same regarding also guidance beam jig-beam part and guidance beam structure. After that quality controls are made by the quality personal. This work presented in the Tales 20, 21 before and after welding. The energy input control system designed by outside expert and welding line operator printed data in the Figs. 23, 24. As regards estimated calculation of cost difference between HSDA guideway and classical embankment rails and cost savings are by outside engineering office. The same regarding variation of measurements in Table 3 and 4 made by companies D and E. Variations before and after welding observed by technical quality inspector of company B. Parameter adjusted by operators in manufacturing processes Tables 16, 17, 18, 19. The use of jig-beam technology in manufacturing guidance beam structure is missing in scientific literature.
The research was carried out in close co-operation with customers. This helped to focus on actual challenges in product development, but made it more difficult to deeply study some details. Hence, balance with engineering and science was a challenge. However, this dissertation has brought new insights in the guidance steel beam design and opened new horizons in high-speed railways.

5.3 Answering the research questions

The research on guideway technology has resulted in knowledge about guideway materials used for guidance, including concrete beam design and structural design requirements. For broader knowledge, the researcher suggests new materials. The researcher also suggests further guideway beam dynamic analysis and opportunities for improving guideways. Also, research is required into large-scale manufacturing processes and automated manufacturing, to see which is more effective (Phelan, 1993).

The comparisons of a steel-beam guidance and manufacturing methods to existing classical rails are presented below (see Table 22). The differences in technologies are seen and focused on the direction of conventional rails. Many separate differences are not presented in this research. It can be said that during this research one answer could be found: classical railway directions do not have strength parameters for cost calculations. The comparison between the steel-beam guidance and classical railway can be calculated to obtain answers to the questions that arise. The manufacturing costs of the steel-beam structure with respect to the advantages of type HSDA are presented (see Table 23 a).

The steel-beam manufacturing method and guidance development represent a new point of view on railway foundation technology. The evaluation of companies A and B conclude that the technology is better focused on future needs in comparison to the existing foundations of classical railways. The steel-beam structure idea was tested, first through a strength/weakness analysis of existing steel beam profiles, and then the I-beam and box-beam profiles were chosen for strength/weakness testing. Diminishing the weaknesses of I- and box-beams and
choosing the strength capabilities of both made sure that the new steel-beam structures and manufacturing method, with energy input control, answered the research question.

**Table 22.** HSDA steel beam Iz-value in relation to classical foundation technology

<table>
<thead>
<tr>
<th>H/B1</th>
<th>HSDA beam moment of inertia in z-z axis Iz [cm4]</th>
<th>Classical embankment foundation of 1-rail (RAMO1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000/2800</td>
<td>6586013</td>
<td>N/A</td>
</tr>
<tr>
<td>2500/2800</td>
<td>6262779</td>
<td>N/A</td>
</tr>
<tr>
<td>2000/2800</td>
<td>5784652</td>
<td>N/A</td>
</tr>
<tr>
<td>1500/2800</td>
<td>5299849</td>
<td>N/A</td>
</tr>
<tr>
<td>1200/2800</td>
<td>4653159</td>
<td>N/A</td>
</tr>
<tr>
<td>1000/2800</td>
<td>4845512</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1. Yield strength ReH (N/mm²) 355-345;
2. Ultimate tensile strength range Rm (N/mm²) 490-630.
3. The parameters are not to be used for dimensional purposes, but only as a rough estimation of the HSDA steel-beam strength value Iz. Higher Iz leads to higher lateral stiffness. Higher lateral stiffness can reduce lateral oscillations and snaking of a train.

The answers of competitive advantages refer to higher lateral stiffness of steel-beam structure (in section 4.1). Comparing long lengths of damp soil foundations to steel-based guidance foundations can be answered by referring to steel-bridge
strength and horizontal strength (section 4.3.3). Solutions provided by this research to classical railway problems include: higher speed, strength against the “snaking” of trains, heavy mass goods, tolerances and factory-made steel beam guidance (see Tables 23, 24).

Table 23. Estimated calculation of cost difference between HSDA guideway and classical embankment rails and cost saving, EUR/km.

a) Railway using HSDA steel beam (two rails): accordingly, company B.

<table>
<thead>
<tr>
<th>Beam type HSDA</th>
<th>Cost (euros/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000/2800</td>
<td>5,600.00</td>
</tr>
<tr>
<td>Foundation and pears</td>
<td>2,987.50</td>
</tr>
<tr>
<td>Total</td>
<td>8,587.50</td>
</tr>
</tbody>
</table>

Details of the cost calculations are kept as a trade secret.

b) Railway using classical embankment (two rails)

<table>
<thead>
<tr>
<th>Embankment</th>
<th>Cost (euros/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>270 m³ a´10</td>
<td>2,700.00</td>
</tr>
<tr>
<td>Width 36 m a´90</td>
<td>3,240.00</td>
</tr>
<tr>
<td>Pears 135 m a´35</td>
<td>4,725.00</td>
</tr>
<tr>
<td>Total</td>
<td>10,665.00</td>
</tr>
</tbody>
</table>

Savings by HSDA euros/m 2,077.50
Savings by HSDA euros/km 2,077,500.00
**Table 24.** Advantages of steel-based foundation over the classical foundation

<table>
<thead>
<tr>
<th>Steel-beam bridge for railways and train applications</th>
<th>Classical foundation (RAMO1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Railway:</strong></td>
<td></td>
</tr>
<tr>
<td>Guidance beams do not need an embankment. Guidance can be used for one or more directions between stations. Saving considerable cost without embankment material, working hours and construction time.</td>
<td>Includes one or more tracks. The track includes ballast with settlement of rolling ground like embankments and cuttings, ditches for water outlets, prevention of frost damage and stabilisation of rail beds, as well as for carrying rail structures. Includes all rail structures.</td>
</tr>
<tr>
<td><strong>Sleepers:</strong></td>
<td></td>
</tr>
<tr>
<td>Beams for HSR do not use sleepers and subsequently many cost savings can be calculated. Also the yearly repair work is minimised.</td>
<td>Sleepers are one of the main components of classical railways.</td>
</tr>
<tr>
<td><strong>Gauge:</strong></td>
<td></td>
</tr>
<tr>
<td>Guidance beam allows different gauges.</td>
<td>Gauge width of 1524 mm is fixed.</td>
</tr>
<tr>
<td><strong>Speed of train:</strong></td>
<td></td>
</tr>
<tr>
<td>Guidance beam structures have very high train horizontal and vertical strength and allow very high-speed trains. Guidance beams can be used for both high- and low-speed maglev trains or urban maglev.</td>
<td>Every track section has a target speed based on rolling stock. The maximum speed depends on the current soil and especially on soft soil circumstances, slow and faster speed variations, but also on the condition of the sleepers.</td>
</tr>
</tbody>
</table>

Continued…..
Traffic cuts
Cross an intersection of highway
Traffic cuts
Traffic on the same level.

**Geometry of railway:**
The guidance beam manufacturing method automated follows the geometry of the railway line in various beam lengths including left/right and up/down curvatures.

**Positioning of tracks:**
Positioning of tracks on HSR guidance at factory.

**Positioning of tracks:**
Positioning of tracks on site on sleepers.

**Ballast:**
No ballast
High cost savings by using the steel beam as a continuous bridge.

**Ballast:**
Railway structure is based on crushed stone or gravel use following many types of cross-section variations.

**Strength calculation:**
Guidance beam strength calculation is according to the guideway plan.
Strength calculations for every millimetres of steel beam guidance sizes.

**Strength calculation:**
Based on various soil types, durability calculations difficult.

**“Snaking” of trains:**
The guidance steel beam structure has a high Iz -value capacity based on co-ordinate system

**“Snaking” of trains:**
Displacement of sleepers is a characteristic of classical rail.

**Cost of rail:**
The cost of every maglev- and HSR rail steel beam can be calculated in accordance with the process of the manufacturing method.

**Cost of rail:**
Unavailable.
5.4 Recommended dimensions for applications

It is possible to use the guidance manufacturing method and guidance steel-beam structure for other practical applications as well, such as: in building industries, steel bridges with metro rails and/or other traffic, ship yards, high rise buildings, power plants, piles, dams, and railway carriage beams, etc. The use of the beam’s strength potential is also turned 180° (see Tables 17, 18).

The steel-beam structures as presented in this dissertation are not restricted to standard dimensions. The practical height and width of the guidance steel beam does not limit the design and manufacturing opportunities or the scope of applications (section 4.2.2). The steel beams’ potentials are presented in section 4.1. The recommended dimensions for applications are on a case-by-case basis (section 3.4.3).

When comparing the bending forces, it can be found that conventional I- and box beam strengths are not good enough for maglev and high-speed rail guidance. The approach presented end-customers with a new structure that has more strength power, which earlier could not be calculated. HSDA, HSDQ, HSDK structures have a very large capacity and are easy to add to by new manufacturing methods (see Figs. 18, 19, 20, 21).

For example, if the HSDA test beam width of a flange (see Table 17) needs to be increased in the construction stage whilst similarly holding other dimensions, it can be calculated by increasing the moment of inertia $I_z \text{ cm}^4$ (see Fig. 15).

The same holds true with HSDQ beams (see Table 18) when they are needed to be increased in the construction stage by a greater moment of inertia $I_y \text{ cm}^4$. By increasing the height, it is possible to calculate various heights incrementally (see Fig. 16).

Also, when holding the upper flange width constant for trains, it is possible to calculate the $I_y$- and $I_z$ -values for various guideways in a country (see Fig. 17).

The steel beam structures and manufacturing methods set new technical requirements in designing and implementation new factory processes for the capacity needed.
5.5 Further research

Based on the results, the following could be considered for future research.

Firstly, further research is suggested to conduct strength tests of existing classical railway embankments in vertical and especially horizontal directions, by taking into account the new forces of increasing speeds of trains and heavy mass goods in transportation on soft soil in a steady state in one country. It should consider the technical specification of the steel-based beam structure as a cost-effective solution for establishing the conditions to enable high speed trains. It is important to consider the steel beam’s potential, for example in arctic railways. (see section 5.4).

The second topic should be to systematically study the advantages of steel-based foundation technology in terms of the design, plan, construction and assembly of new technology, and to establish organisations of new international maglev- and high-speed or higher speed guideway institutes for global transportation (see section 3.1.2).

Thirdly, consideration should be given to updating the European Standards requirements by adding steel-based beam structure foundation capability potential against vibration, as an example of maglev guideway and HSR potential based on the co-ordinate systems of members (see section 4.1).

Fourthly, the process automation of energy input measurement systems in manufacturing steel bridges and railway bridges should be considered in the standards (see section 4.5).
6. CONCLUSION

This dissertation focuses on a new steel beam and a new manufacturing method. The railway foundation review presents the existing railways as on embankments. Classical railway embankments are limited to lower speeds, because of the soft and damp soils in various areas of many countries. High-speed rail and maglev rail steel-beam guidance has not been considerably researched. International literature is looking at efficient transport infrastructures for cities and regions. Studies of high-speed railway and maglev train magnetic underbodies in literature are focused on the new need for steel-based foundations. The existing guidance manufacturing methods have used concrete guideways based on available local material. Most of the maglev literature details the development of trains, but not guideways. In general, speed in the literature is considered in terms of trains, neglecting the influence of rails on speed. This data is crucial to be able to efficiently develop beam structure and manufacturing methods. This dissertation focuses on the product, manufacturing method and applications.

The literature shows that there is a need for new railway technology. Classical foundation technology has problems in reaching high speeds and allowing for the mass of freight. It is important to investigate railways from the new point of view of steel-beam railway bridges. The development of steel-beam structures and manufacturing include the analyses of distortion, the welding process, mechanical performance, tests of profiles and the new profile co-ordinate system. Consequently, energy measurement technology during continuous welding is the most important. The method included the development of the new branch and focus on the competitive nature of steel-based track foundations.
The cost-saving technology using steel-based track foundations was developed. The beam capability and cross-sectional properties of HSDA, HSDQ and HSDK structures were presented. Differences in the strength of the steel beams compared to the classical foundation parameters were calculated. Classical foundation parameters could not be identified in the literature. Moreover, tight tolerance requirements in the manufacturing processes could be reached by submerged longitudinal arc welding. The new control system contributes to the conventional SAW welding procedure specification WPS. The energy input control system of SAW welding in the manufacturing process, which was developed in this dissertation, did not previously exist. The large strength capacity of the steel beam structures results in cost-saving technology for various span lengths of steel bridges in comparison to classical embankment foundation railways.

An energy input system was utilised in the manufacturing method developed. It was adapted to control the amount of energy input to the seam, in all or some of the seams. The equipment was also adapted to keep the energy values exactly the same or substantially the same. When the cost of a steel-beam guidance and manufacturing method was compared to the cost of existing classical railways, the classical railway did not have exact parameters for cost calculations. However, the cost of a steel-beam guidance could be calculated for every millimetre size of steel beam guidance in factory. Also, there was the requirement of adaptability to snaking caused by high-speed trains. The comparison of long lengths of damp soil foundations to steel-based guidance foundations, can be answered by referring to the steel bridge strength and horizontal strength.

Based on the research and obtained results in this dissertation, the contributions can be summarized as follows: 1) steel-based foundation competitiveness compared to classical railway foundations are presented, 2) new manufacturing methods for design of the steel-beam structures are presented, 3) the mechanical strength of cross-sectional properties of profiles are presented, 4) a new energy input control system in the manufacture of steel-beam structures for maglev, high speed rail, railway bridges, and applications is presented.
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Ordinary embankments have limited applicability as support structures for high-speed trains. In rail traffic, the need to develop rapid transport connections has largely focused on the manufacture of high-speed train technologies, more so than tracks. This dissertation addresses how the development of a continuous steel railway beam bridge can help to solve the problems of classic railways and high-speed train railways. The work aims to develop a steel railway beam for maglev and high-speed train applications in order to solve the research question. Due to the technology employed in this research, ordinary methods cannot be used to manufacture a continuous steel-beam railway bridge. This is due to the tight tolerances and the necessity of economical manufacture. The product idea and manufacturing method have been developed as an integrated process between companies, in which the end client perspective has been determined by analysing the railway beam structure and the efficient manufacturability of the beams. This dissertation demonstrates that the steel railway beam has been developed as a product structure and manufacturing method system.