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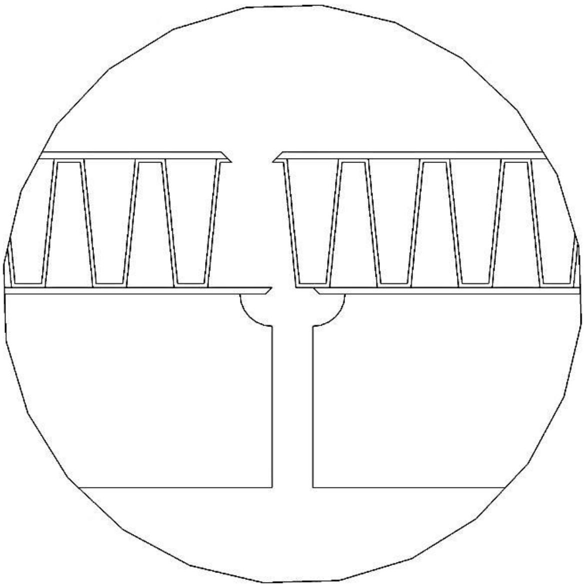

Element to element joints of corrugated core steel sandwich bridge decks

Master of Science Thesis in the Master's Program Structural Engineering and Building Technology

TOBIAS ADOLFSSON

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Master's Thesis 2016:4

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Cover:
Figure showing a principle connection between steel core sandwich elements (SSE)

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Göteborg, Sweden 2016

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ABSTRACT

Traditionally, orthotropic stiffened steel decks have been the solution for designing of steel bridges. With new technology comes the possibility to develop steel design. By the technique of hybrid laser welding it has been made possible to replace the orthotropic stiffened steel decks with steel sandwich elements. Through the use of steel sandwich elements, the dead weight of the structure is reduced with a longer life and without decreased stiffness.

Steel sandwich element consists of two thin sheets as and a steel core. With the technology available in laser welding better fatigue strength and a greater degree of prefabrication can be achieved.

Studies have shown that steel sandwich elements can be designed to meet the structural requirements. But because of the conditions of production and transportation of elements, steel sandwich elements are spliced in the steel shop and joined on the construction site. In this study the conditions that exist in terms of transport and production are discussed. Also how a bridge system with a steel sandwich bridge deck behaves depending on the orientation of the steel core is discussed, and how this affects the connection design.

Through a quantitative process, a number of proposals for connections between steel sandwich elements have been developed. In an evaluating process this large number of proposals was reduced to a few promising ones with respect to structural and client demands.

Keywords: Steel sandwich elements, bridge decks, joints, SSE

Anslutningar mellan stålsandwichelement

Master of Science Thesis in the Master's Program Structural Engineering and Building Technology

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SAMMANFATTNING

Traditionellt sett har ortotropiska ståldäck varit lösning för brokonstruktioner med stålfarbana. Med ny teknik kommer möjligheten att utveckla stålbyggandet och genom hybridlasersvetsning har man kunnat visa på möjligheten att byta ut de orotropiska ståldäcken till förmån för stålsandwichelement. Genom användningen av stålsandwichelement kan egenvikten i konstruktionen reduceras med en ökad livslängd och utan att ge efter på bärigheten.

Stålsandwichelementet består av två tunnare plåtar som mellanlagras av en korrugerad stålplåtskärna. Ett system som resulterar i låg egenvikt och hög styvhet. Med tillgänglig teknik inom hybridlasersvetsning kan man uppnå ökad utmattningshållfasthet och en större prefabriceringsgrad.

Studier har visat på att stålsandwichelementen kan designas för att uppfylla de strukturella krav som eftersträvas. Men på grund av förutsättningar inom produktion och transport av elementen måste stålsandwichelement skarvas på arbetsplatsen. I denna studie avhandlas vilka förutsättningar som finns när det gäller transport och produktion. Men också hur ett system brosystem med stålsandwichelement som brofarbana beter sig beroende på stålsandwichelements orientering. Och hur detta påverkar anslutningens utformning och systemets verkningssätt.

Genom en kvantitativ process har ett antal förslag till anslutningar mellan stålsandwichelement tagits fram. I samarbete med WSP Bridge engineering och Chalmers har dessa alternativ bantats ner till ett antal lovande som utvärderas med avseende på ett antal design- och beställarparametrar.

Nyckelord: Stålsandwichelement, brobana, anslutningar, SSE

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Preface

This thesis, covering the prelude of joining steel core sandwich elements, was carried out during June 2015 and December 2015 at WSP Bridge engineering in Göteborg.

The project has been a valuable experience to me. The opportunity of working among engineers at WSP bridge engineering has given a lot more than just the knowledge of joints between steel core sandwich elements. Thank you everyone at WSP bridge engineering for taking care of me during this period. I wish you the best of luck in the future and hope to work besides you again one day.

I would like to thank my beloved family and my friends for all the support. I would not have made it without you.

MSc. Peter Nilsson, thank you for your encouragement during the project. And thank you associated Professor Mohammad Al-Emrani for sharing your great knowledge with me. Also a special thanks to my beloved friend Philip Radtke for the valuable feedback and all the great moments we have shared so far.

Tobias Ingvar Adolfsson

Göteborg
Juni 2016

Abbreviations

CO_2	Carbon dioxide
DFMA	Design for manufacturing and assembly
ESL	Equivalent single layer
FEM	Finite element method
FRP	Fiber reinforced polymers
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HLAW	Hybrid laser arc welding
LM1	Load model 1
MAG	Metal active gas
MIG	Metal inert gas
Nd:YAG	Neodymium-doped-yttrium-aluminium-granet
SLS	Serviceability limit state
SSE	Steel sandwich element
TIG	Tungsten inert gas
ULS	Ultimate limit state

Roman letters

E	Modulus of elasticity [Pa]
E_x, E_y	Modulus of elasticity in x- and y-direction respectively [Pa]
G_{xy}, G_{xz}, G_{yz}	Shear stiffness respectively [Nm]
Q_k	Characteristic axel load [N]
l_{SSE}	Length of SSE [m]
w_{SSE}	Width of SSE [m]
h_{SSE}	Height of the corrugated steel core sandwich profile [m]
h_c	Height of the steel core [m]
t_c	Thickness of the steel core [m]
t_{ftop}	Thickness of the top flange in the sandwich profile [m]
t_{fbot}	Thickness of the bottom flange in the sandwich profile [m]
f	Length of the flat section in the corrugation [m]
q_k	Uniform distributed load [N/m^2]

Greek letters

α_q, α_Q	Adjustment coefficient
Ψ_{1q}, Ψ_{1Q}	Reduction factor
ν	Poisson's ratio [-]

1 INTRODUCTION

1.1 Background

During the past decades the way of constructing steel bridge decks has not changed in any big manner. An orthotropic steel deck consists of a steel plate with a number of ribs welded to it. The ribs, that can have both closed and open cross-sections, acts as stiffening members of the plate.

Because of the many welds and the complex geometry used in this traditionally orthotropic steel deck, the deck becomes sensitive to fatigue. And the high stress concentration makes this design likely to experience fatigue cracking. Due to this the orthotropic decks often need more maintenance, and have higher service life cost.

The steel core sandwich element (SSE), which was developed in the marine and aviation industries, could be the key to shortened construction times, fewer problems with fatigue and a higher stiffness-weight ratio of the bridge deck structure. These steel sandwich elements are prefabricated using faces of steel plates which are joined together with a steel core in between. The steel core could be of any profile however, for the use of steel sandwich elements as bridge decks it has been show that the most promising core profile is the one made out of a corrugated steel plate. The bending moment in the element is carried by a force couple a longer distance from the center of rotation. And the inclined webs of the corrugated core transfers the transversal shear force. (Kujala & Klanac, 2005)

Until recently the limitations of traditional welding methods has been the hindering of the development of the SSE concept. With the method of hybrid laser arc welding (HLAW) the production of SSE becomes feasible and cost efficient. The HLAW combines laser welding with traditional arc welding, yielding an increased efficiency and weld quality. Hence the opportunity to implement SSE in bridge construction is feasible.

1.2 Project aim

This master thesis project aim is to present the prerequisites for development of a joint between corrugated core steel sandwich elements. And also to point out the requirements and conditions for development of joints between corrugated core steel sandwich elements and propose a number of joint geometries.

1.3 Method

The background to and history of the steel sandwich elements are covered in the literature study together with the performance of the elements as a structure. The production method and procedure of SSE are presented together with the production method and procedure of building short span bridges and launched medium span bridges.

By taking advantage of the knowledge of how bridges are built today a number of alternatives of joints for the SSE are developed during a process where a large number of joint geometries are proposed in a starting quantitative phase. The proposals are evaluated and reduced to a number of qualitative ones. The most promising alternatives are presented as proposed solutions.

1.4 Outline

The first chapter introduces the thesis and presents the purpose of the project. After that chapter two follows, covering the literature study. In the literature study the concept of SSE is investigated together with the production process and transport prerequisites for SSE. Different methods of bridge building with production methods and their requirements are covered. Also the method of Design for manufacturing and assembly (DFMA) is discussed here.

In chapter three the joint alternatives are presented. The concepts of SSE are divided into categories based on the geometrical constraints. And the joints occurring in the system are presented and sorted by joint type. The bridge deck configuration is described and a FE-analysis is carried out to clarify the structural behavior of for the SSE depending on the concept.

In the following chapter four the conceptual joints are presented for each joint type. A quantified process of producing joint concepts has been carried out and the most promising alternatives are presented and described for further evaluation.

Chapter five covers the evaluation of the joint alternatives presented in the previous chapter. By using an analogy to the DFMA the alternatives are given a score and the best alternative of each joint type is presented.

In chapter six the process of developing joint alternatives is discussed and in chapter seven conclusions based on the results of the project is drawn.

1.5 Limitations

This thesis is limited to treat only the element to element joint itself with less or no further structural analysis. The joint is evaluated based on the designer, contractor and the client's requirements.

The project is limited to cover conventional joining techniques as of today; therefore no joint solutions using adhesives are investigated.

In order to make the investigation easy to survey only two girder bridge systems will be treated.

2 LITERATURE STUDY

This literature study covers the subject of production of the steel sandwich plates, the production of short span steel bridges and the production of launched medium span steel bridges. The handling process and prerequisites for transportation is also studied. A method used for evaluation is the 'Design for manufacturing and assembly' which can be used to evaluate the joints between SSE.

2.1 Introduction to SSE

Steel sandwich plates are element built up from two faces joint together with a core that could be made out of steel or an elastomer. By placing the load bearing material away from the neutral axis, as shown in Figure 2 – The "sandwich effect" , a stiff structure is obtained and the possibility to produce elements with a good stiffness-weight ratio is achieved. By this configuration the weight of the elements can be reduced with about 30-50 % in comparison to conventional steel structure. By creating a larger distance to the neutral axis the second moment of area is increased significantly. Hence the bending stiffness is increased while the self-weight becomes slightly larger (Beneus & Koc, 2014).

Steel sandwich plates can be constructed with different core configurations. It has been shown that the corrugated core is superior for use in bridge construction. This is preferred by designer due to the high overall stiffness together with the relatively easy welding procedure (Alwan & Järve, 2012).

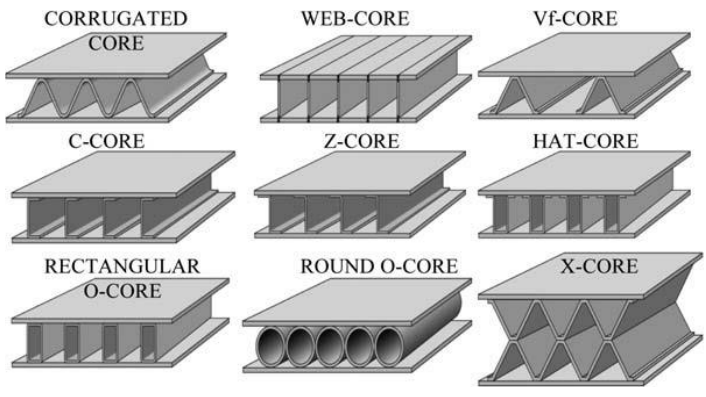


Figure 1 – Steel sandwich elements core configuration (Kujala & Klanac, 2005)

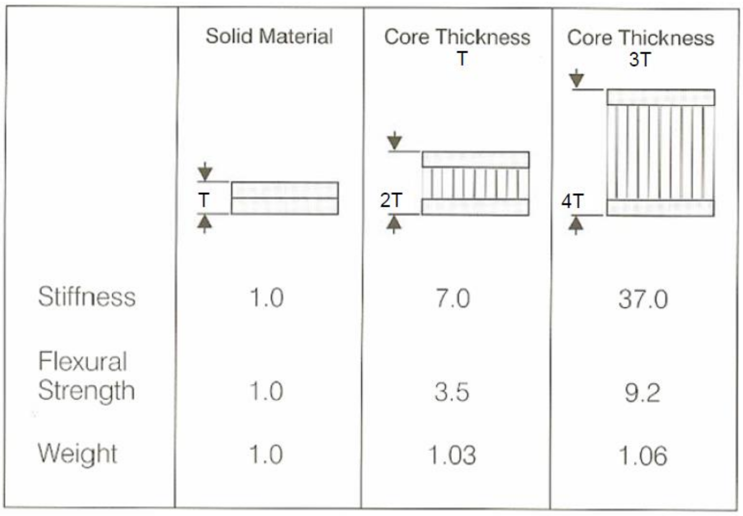


Figure 2 – The ”sandwich effect” (SANDCORE, 2005)

The proposal of using steel sandwich elements was made as early as the 1950’s. Due to lack of knowledge in welding steel elements together the SSE did not gain any ground in the industries. The welding techniques known at the time was both inefficient and expensive. During the 1980’s the American navy developed the laser welded steel sandwich element. In the beginning of the 1990’s these sandwich elements where first used in the warship Mt. Whitney. These structural elements had great performance and the total weight of the ship could be reduced by 40 %. However, the project of building ships using sandwich elements was abandoned as there was no manufacturer that could produce SSE to a reasonable cost at the time (Alwan & Järve, 2012).

2.1.1 Production of SSE using Hybrid Laser Arc Welding (HLAW)

Hybrid laser arc welding (HLAW), also known as laser hybrid welding or hybrid welding, where first introduced in the 1970’s by combining laser beam welding with arc welding. The common choice of laser for laser hybrid welding has been high power continuous-wave lasers such as the solid-state neodymium-doped-yttrium-aluminum-garnet (Nd:YAG) and the Carbone dioxide laser (CO_2). Other laser welding methods that can be used in HLAW is fiber laser, thin disk laser and semiconductor diode laser (Brian, 2011).

A number of advantages from the two different methods, laser welding and arc welding are combined using hybrid laser welding. This yields an efficient welding method producing cost-efficient welds at a high speed with minimal distortion. Hybrid laser arc welding produces reliable joints with a long fatigue life and low risk of corrosion (Abbott, et al., 2007).

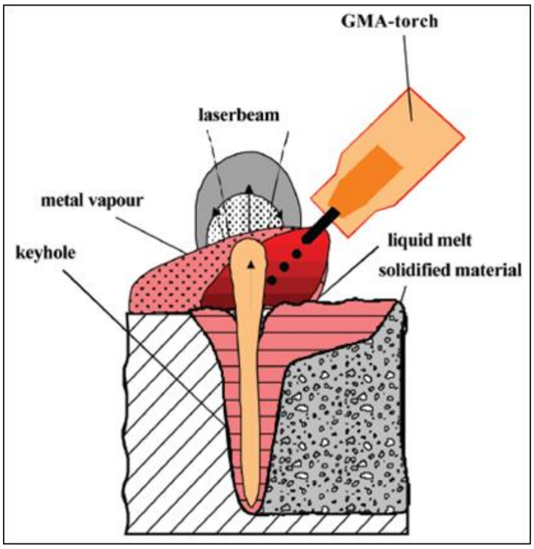


Figure 3 – Principle of the hybrid laser welding (Zhou & Tsai, 2012)

The production of steel sandwich is carried out in a steel shop. The dimension of the steel sandwich plate depends on the plate dimensions possible to produce in the steel plant. The production is carried out in two steps presented in the list below.

1. The corrugated web plate is placed upon one of the steel faces and welded using HLAW from the “inside” of the corrugated plate.
2. The second face is placed on the element and is welded using HLAW from “outside” of the face.

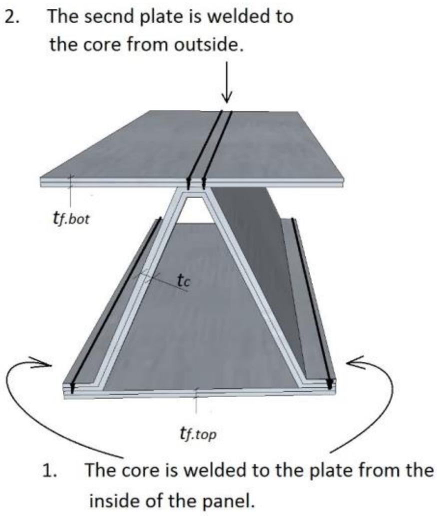


Figure 4 – Schematic figure showing the production process (Beneus & Koc, 2014)

The dimensions of SSE possible to produce are highly dependent on a number of criteria; the dimensions of the input material, transportation on public roads, handling on the construction site and limitations of the HLAW production cell. One producer that can produce SSE today is Kleven Maritime AS. According to Simon Sundal, Automation engineer on Kleven, the maximum dimension available today is 2500x8000mm^2.

The maximum dimensions that can be transported on the public roads in Sweden are regulated by the Swedish transport agency (Transportstyrelsen). Two publications are available regulating the dimensions of length and width. The width regulations are published in TSFS 2010:141 and the length regulations in TSFS 2010:142 (Transportstyrelsen, 2010).

According to the Swedish transport agency the maximum width that can be transported without a special permit is 3500 mm. However, if the width is larger than 3100 mm the regulations in chapter 2 and chapter 3 of TSFS 2010:141 must be fulfilled. The requirements for transporting widths of 3100-3500 mm including for example speed regulations at 40 km/h and other special arrangements as an escort car (Transportstyrelsen, 2010).

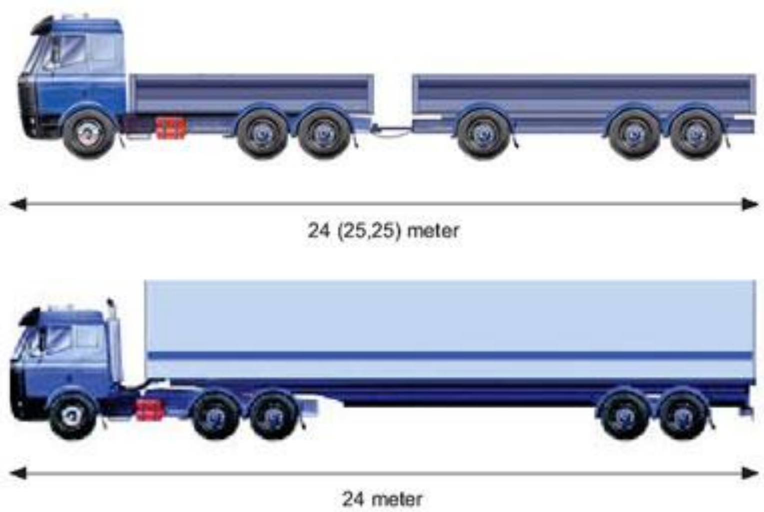


Figure 5 – Figure showing the maximum allowed lengths (Transportstyrelsen, u.d.)

The length shown in figure 5 is the maximum allowed road train lengths on Swedish roads without special regulations according to the Swedish transport agency. The longest permitted road train possible without special permits is, according to TSFS 2010:142, 30 meter. For lengths more than 24 meter there are a number of regulations needed to be fulfilled. (Transportstyrelsen, 2010)

- Up to 24 meter road trains – No extra regulations
- From 24 meter up to 30 meter road trains – Regulations in TSFS 2010:142 must be fulfilled

SSE with a length of up to about 20-26 meters can be transported without any further regulations. For SSEs with a length of about 20-26 meters can be transported without special permit but according to the extra regulations in TSFS 2010:142. (Transportstyrelsen, 2010)

The regulations apply where the load is indivisible. The definition of an indivisible load according to the Swedish transportation administration is “A load that cannot be divided into two or more partial loads without the risk of unnecessary costs or damages” (Trafikverket, 2014)

A summary of for which lengths and widths the regulations apply is shown in Table 1 – Lengths and widths of the road train there is extra regulations in the TSFS

Table 1 – Lengths and widths of the road train there is extra regulations in the TSFS

	Width < 2600 mm	2600 mm < Width < 3100 mm	3100 mm < Width < 3500 mm
Length < 24000 mm	No extra regulations	Extra regulations concerning wide indivisible load, TSFS 2010:141	Extra regulations concerning wide indivisible load, TSFS 2010:141
24000 mm < Length < 30000 mm	Extra regulations concerning long indivisible load, TSFS 2010:141	Extra regulations concerning both wide and long indivisible load, TSFS 2010:141 and TSFS 2010:142	Extra regulations concerning both wide and long indivisible load, TSFS 2010:141 and TSFS 2010:142

2.2 Possible fastening methods for joining of steel elements

There are a number of possible fastening methods for the purpose of joining steel today. The most common ones are presented below.

Welding

The welding technique has been known for a long time and the performances of different type of welds are well documented. By welding steel together a good interaction is obtained for the structure. The welding process can, however, for complex geometry be costly and hard to perform with adequate quality on the construction site.

Mechanical fastening

Mechanical fastening was the first method to be used in bridge construction. By bolts the elements are fastened together forming connections which can be, depending on the joint configuration, both moment free or stiff.

2.3 DFMA – Design for manufacturing and assembly

Design for manufacturing and assembly is a method used in for example automotive and aerospace industries to effectively meet the requests of the client and the designer. The aim of DFMA is to ease the manufacturing of parts that will form a production and simplify the design of the production with respect to the assembly. The method is based on close communication between the designer and the manufacturer throughout the project (Mara & Kliger, 2015).

There is a wide range of proposed criteria for evaluation. For the purpose of evaluation joints between fiber reinforced polymers (FRP) elements some of the criteria presented in the list below can be chosen and applied in the process together with client based requirements and demands (Mara & Kliger, 2015).

For the purpose of evaluating alternative concepts a number of generalized DFMA criteria can be used (Kalyun & Wodajo, 2012):

- Simplify design and reduce the number of parts
- Standardize and use common parts and materials
- Mistake-proof product design and assembly
- Design for ease of parts orientation, handling and assembly
- Design for efficient joining and fastening
- Design for manufacturing and ease of fabrication
- Design to avoid unneeded surface finish requirements

2.3.1 Client requirements

In order to obtain the best fitted joint the requirements of the client must be taken into account together with the design requirements. The requirement of the client is stated below (Mara & Kliger, 2015):

- Rapid bridge construction: Short construction time
- Affordable: Cost efficient and economical
- Modular assembly: The system should be designed to be possible to assemble by modules
- Maintenance free: The joint should be designed to be as maintenance free as possible
- Easy inspection: The joint should be easy to inspect during its life time
- Quick repair/replacement: The joint should be designed to be easy to repair or replace
- Low environmental impact: A solution with low noise and vibrations
- Low energy solution: The solution should consume low energy and produce as little carbon dioxide as possible
- Safe: The safety of the joint in terms of construction and during the lifetime

2.3.2 Design requirements

Some requirements on the design are controlled by law or standards. The requirements that must be fulfilled for all connections are stated below (Mara & Kliger, 2015):

- Construction life of 50-100 years
- Requirements regarding design in the ultimate limit state (ULS) and the serviceability limit state (SLS)
- Easy to repair and maintain
- Reasonable price and acceptable environmental impact
- Other regulations like Eurocode

For the design of the joint the requirements can be expressed as follows with

- Tolerances: The right tolerances
- Reduced number of parts in assembly: By reducing the number of parts to be assembled the risk of mistakes is reduced and the design procedure is simplified.
- Mistake-proof connection: The joints should be designed to fit only in on certain way to minimize the risk of mistakes in the joining.
- Minimize movement and rotation: To move and rotate parts is non-value creating actions. This should be reduced to keep the assemble process cost effective and rapid.
- Safety during construction: The pars should be designed to be safe for workers and other materials. Eg. Sharp edges should be avoided.
- Standardization: Less inventory cost and less additional evaluation and experimentation is needed. By standardization the cost can be reduced.
- Avoid time-consuming joints: The difficulty of joints

2.3.3 Evaluation using DFMA criteria analogy

By implementation of the DFMA criteria and the client requirements a matrix of relative importance can be formed. This is a way of consolidating the requirements of design, clients and norms into one and makes it possible to evaluate the proposed solutions against one and other in an easy way.

2.3.3.1 Relative importance matrix

By deciding the importance of the client's requirements and find the relation to the design requirements the relative importance of each design requirement can be found. For the purpose of evaluation the design requirements is used with the relative importance to represent the client's demands as well as the design requirements (Mara & Kliger, 2015).

The weighting presented in table 1 shows the strength between the client and the designer demands. The score is defined as 1: weak to 9: strong.

Table 2 – Translation of the client requirements to design requirements, 1: weak, 9: strong (Mara & Kliger, 2015)

Client requirements	Voice of the client	Design requirements										
		Tolerance	Minimize on-site bonded connections	Maximum repetition of the connection detail	Provide sealing	Reduce number of parts	Provide disassembly	Mistake-proof connection	Minimize movement and rotation	Avoid sharp edges	Standardisation	Avoid time consuming fasterner
Rapid bridge construction	8	9	9	4		4		9	1	1	9	9
Affordable	8	4	9	9	4		1	4			9	4
Modular assembly	5			4			4	1			4	
Maintenance free	6		1		9	1			4			
Easy inspection	9			4		4	1				1	1
Quick repair/replacement	9		9				9				1	4
Low environmental noise and vibration solution	5	4		1		1			1			
Low energy and CO_2 solution	5	1	1	1			4				4	
Safe	9	1	9	1				4	4	9	4	
Absolute importance		138	317	179	86	79	138	145	73	89	238	149
Relative importance		**8%**	**19%**	**11%**	**5%**	**5%**	**8%**	**9%**	**4%**	**5%**	**15%**	**9%**

2.3.3.2 Evaluation of concepts

The relative importance of the relation between the client's demand and the design requirements are used to evaluate the concepts. By using the relative importance from the requirements of the clients and the DFMA requirements the joint concepts can be easily evaluated.

Table 3 – Example of evaluation based on the design requirements (Mara & Kliger, 2015)

Design requirements	Relative importance	Connection concept			
		Connection 1	Connection 2	Connection 3	Adhesively bonded connection
Tolerance	8%	1	1	3	5
Minimize on-site bonded connections	19%	4	1	4	1
Maximum repetition of any connection detail	11%	5	5	5	5
Provide sealing	5%	2	3	4	4
Reduce number of parts	5%	4	4	5	4
Provide disassembly	8%	5	3	5	1
Mistake-proof connection	9%	5	4	5	3
Minimize movement and rotation	4%	1	3	5	3
Avoid sharp edges	5%	5	2	4	2
Standardization	15%	2	3	4	3
Avoid time-consuming fasteners	9%	5	5	5	5
Total score		3,6	2,9	4,4	3,1

In order to make the process of evaluation more straight forward and clear the alternatives to be evaluated are given 1-5 points. The definition of the scale for each design requirement is presented in the table below.

Table 4 – Evaluation of concepts (Mara & Kliger, 2015)

	Score definition	
Design requirements	**1**	**5**
Tolerance	Very low tolerance	High or irrelevant tolerance
Reduced number of parts in assembly	Many parts to be assembled	One part only
Mistake-proof design	Can be assembled in different ways	One-way assembly
Minimize movement and rotation	A lot of movement and rotation in assembly	No movement and rotation
Standardization	Not standardized at all	Fully standardized
Avoid time consuming joints	Many fasteners	No fasteners

3 CONCEPT ALTERNATIVES

For the purpose of using SSE as bridge deck in a two girder steel bridge system there is two possible categories of solutions. The SSE can be either oriented with the core longitudinal direction in the main girders direction or perpendicular to the main girders.

For the concept of a bridge with a two girder system the choice of orientation of the SSE is decisive for the type of joints needed. Hence the dimensions of SSE are strictly regulated from the manufacturer and transport we can divide the two girder system with SSE deck into a couple of different alternatives.

Due to the orthotropic behavior of the SSE the orientation of the bridge deck will affect how the structural system is working and how the load is transferred from the load to the substructure.

3.1.1 Element to element joint types

The geometry of the corrugated core SSE gives us two types of element to element splices possible to occur depending on the of the steel deck;

- *Joint A*: Element to element joint in the transversal direction of SSE shown in Figure 6
- *Joint B*: Element to element joint in the longitudinal direction of SSE shown in Figure 7

The joint of Type A is defined as the joining of SSE in the transversal direction of the element as shown in Figure 6 – Element to element joint in the transversal direction .

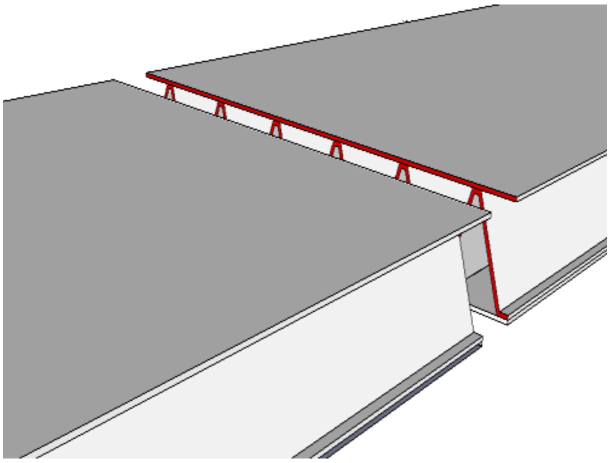


Figure 6 – Element to element joint in the transversal direction (Beneus & Koc, 2014)

Due to the cross-section of the SSE this joint is the more complicated of the two types to produce. In order not to disturb in the manner the SSE is carrying the load the best solution would be to have full interaction all over the cross-section. This is not possible due to the narrow accessibility during production.

The Type B joint is defined as the joint in the SSE longitudinal direction as shown in Figure 7.

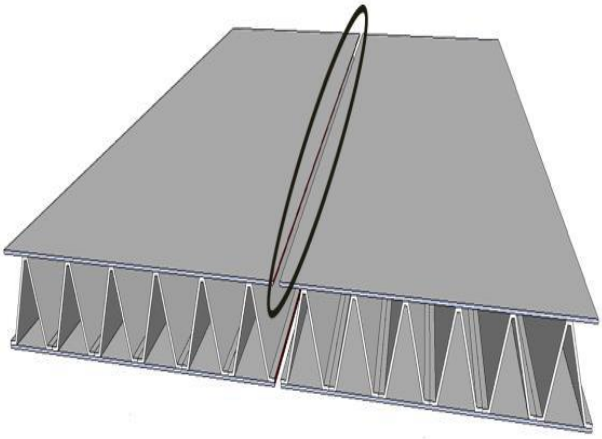


Figure 7 – Element to element joint in the longitudinal direction (Beneus & Koc, 2014)

3.1.2 Definition of concepts and concept categories

The geometrical aspect of the maximum available dimensions of SSE will be governing for dividing the concepts into eight different categories from A to H. For these eight categories we will have four different configurations in terms of joint setup.

Table 5 – Possible configurations depending on the bridge geometry

		Orientation of SSE	Bridge length, l_{bridge}	Bridge width, w_{bridge}	Joint A	Joint B
Category 1	A	Longitudinal	$< l_{SSE}$	$< w_{SSE}$		
	B	Longitudinal	$< l_{SSE}$	$> w_{SSE}$		x
	C	Longitudinal	$> l_{SSE}$	$< w_{SSE}$	x	
	D	Longitudinal	$> l_{SSE}$	$> w_{SSE}$	x	x
Category 2	E	Transversal	$< w_{SSE}$	$< l_{SSE}$		
	F	Transversal	$< w_{SSE}$	$> l_{SSE}$		x
	G	Transversal	$> w_{SSE}$	$< l_{SSE}$	x	
	H	Transversal	$> w_{SSE}$	$> l_{SSE}$	x	x

3.2 FE-Analysis of SSE in a two girder system

In order to present the difference between the concepts a FE-analysis was conducted using Brigade/PLUS 5.2. The SSE used as a top flange and bridge deck in the system was varied and analysis was carried out for the two cases

- Longitudinal orientation of the SSE (Category 1)
- Transversal orientation of the SSE (Category 2)

The SSE of interest, with a corrugated steel core, has an orthotropic behavior. The geometrical properties and the level of orthotropic properties of such a plate will highly effect the load effect distribution. The source of the orthotropic behavior is the lower transversal shear stiffness in the direction orthogonal to the core longitudinal direction. Due to this the orientation of the plate is relevant.

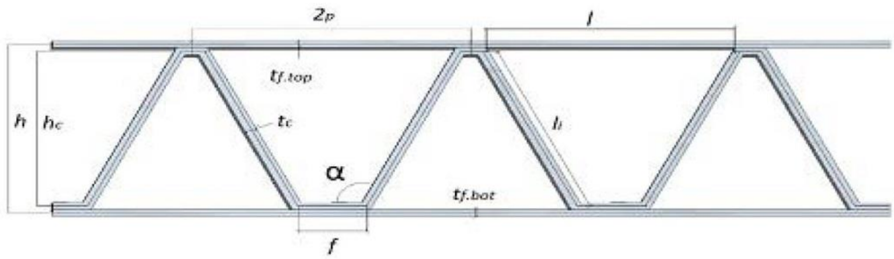
By using a FE-model the behavior of the structure can be shown in a simplified manner. This type of FE-modelling of SSE has been carried out by e.g. (Beneus & Koc, 2014) and (Dackman & Ek, 2015).

Precise stress detection was not of interest; hence the model can be built up by using an equivalent single layer (ESL). The needed sectional constants obtained using by the Mathcad routine created by (Beneus & Koc, 2014) and further developed by (Dackman & Ek, 2015).

The ESL representation of the SSE was modelled on line supports representing the main and transversal girders in the bridge system. By altering the material direction of the elements the SSE-deck could be represented either in the bridge longitudinal direction or in the transversal direction. The SSE deck is assumed to be simply supported; hence the stresses from global bending can be neglected.

3.2.1 Material model

For the purpose of this FE-investigation the material model used was of lamina type. This choice enables out of plane bending and shear induced deformations was included, i.e. Riessner-Mindlin kinematics. A translation from a SSE element with certain geometry was carried out to obtain the equivalent engineering constants for the lamina shell elements.



SSP model

Dimensions

h_{SSE}	237 mm
h_c	222 mm
t_c	7,2 mm
t_{ftop}	8 mm
t_{fbot}	7 mm
α	114,6 deg
f	40 mm

Materials

Material behaviour		Elastic
Type		Isotropic
E	v	
210 GPa	0.3	

Eqvivalent singel layer shell model

Materials

Material behaviour		Elastic			
Type		Lamina			
E_x	E_y	v_{xy}	G_{xy}	G_{xz}	G_{yz}
50,95 GPa	38,83 GPa	0.3	14,594 GPa	6,078 GPa	0,569 GPa

Sections

Type	Shell, Homogeneous
Section integration	During analysis
Thickness	0.247 m
Thickness integration rule	Simpson
Thickness integration number	11

Figure 8 – Material and geometry data for the FE-model (Beneus & Koc, 2014)

3.2.2 Load model

According to Eurocode SS-EN 1991-2 load model 1 covers the most effects of traffic loads from heavy traffic and normal traffic. This model is used for global calculations.

Load model 1 consists of two groups of loads

1. The first group consisting of a tandem system, with two bogie axles, each with an axel load of $\alpha_Q Q_k$, where α_Q is an adjusting factor.
2. The second group consisting of an evenly distributed load $\alpha_q q_k$, where α_q is an adjusting factor.

The bridge deck can be divided into lanes according to table 4.1 in Eurocode SS-EN 1991-2, here shown in Table 6 – Number of lanes possible for different with of the bridge deck.

Table 6 – Number of lanes possible for different with of the bridge deck

Carriageway, w [m]	*Number of lanes, n*	*Width of one load field*	*Remaining width*
w < 5.4 m	n=1	3 m	w - 3 m
5.4 < w < 6m	n=2	w/2	0
6 m < w	n=int(w/3)	3 m	w – 3 x n

From figure 4.2b in Eurocode 1991-2 the contact area for the wheels in contact with the bridge deck should be taken as 0.4 x 0.4 m^2. The load is spread out through the asphalt cover with an angle of 45º.

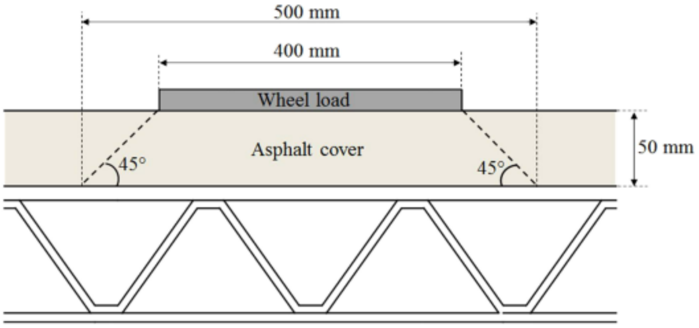


Figure 9 – Principal figure of contact area under patch loading (Dackman & Ek, 2015)

According to TRVK Bro 11 deformations should be calculated using the frequent value in the load combination. The coefficients α_Q and α_q are national parameters and was chosen to 1. The same holds for Ψ_{1Q} and Ψ_{1q}, which is also taken as 1.0 (Trafikverket, 2011).

Table 7 - Load combination for load model 1 in Eurocode

	Q_k [kN]	q_k [kN/m^2]	α_Q	α_q	Ψ_{1Q}	Ψ_{1q}	$\alpha_Q\Psi_{1Q}Q$ [kN]	$\alpha_q\Psi_{1q}q$ [kN/m^2]
Lane 1	300	9	1.0	1.0	1.0	1.0	300	9
Lane 2	200	2.5	1.0	1.0	1.0	1.0	200	2.5
Lane 3	100	2.5	1.0	1.0	1.0	1.0	100	2.5
Remaining area	0	2.5	-	1.0	-	1.0	-	2.5

3.2.3 Geometry of the FE-model

The geometry of the FE-model was taken from a real bridge of today. The bridge over Bergeforsen was used in earlier studies carried out by (Dackman & Ek, 2015).

The total length of the bridge is 166 meters which is divided into three spans. The total width of the bridge is 11.25 meters. The distance between the main girders is 6 meters and the distance between the transversal beams are 9 meters.

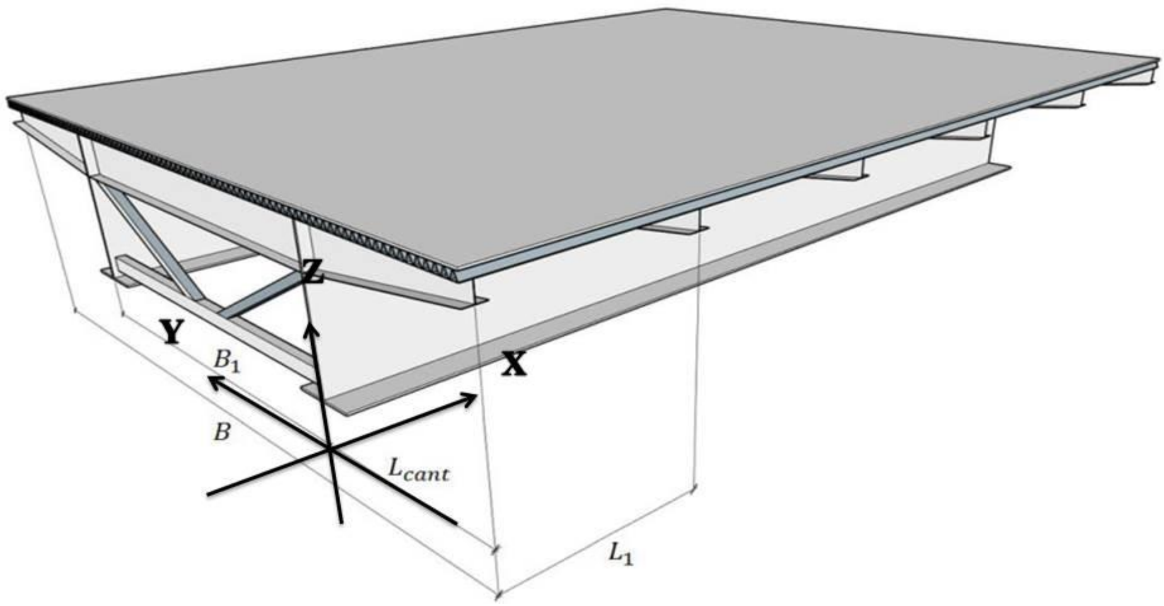


Figure 10 – Segment of a bridge over Bergeforsen (Dackman & Ek, 2015)

The x-axis of the system is parallel to the longitudinal direction of the bridge. The y-axis is perpendicular to the length direction of the bridge. The z-axis is vertical and positive upwards.

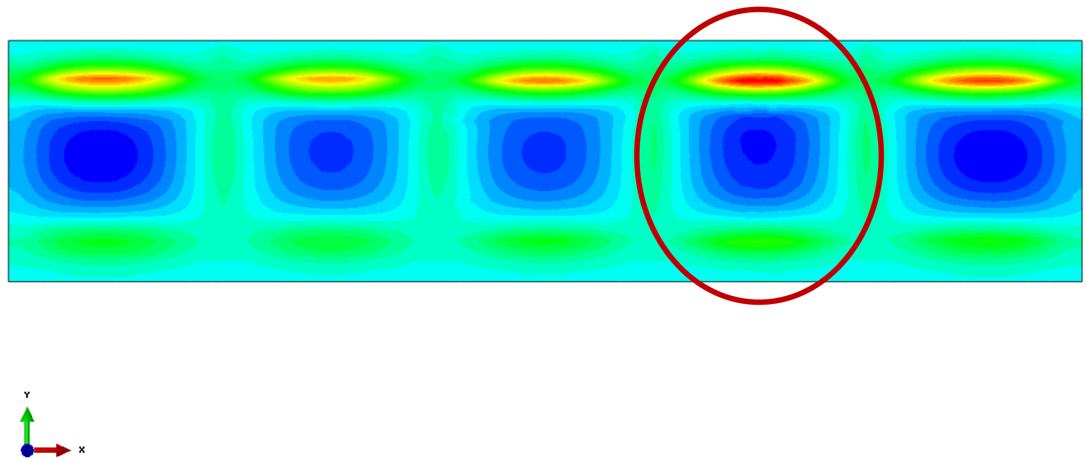


Figure 11 – FE-model showing sectional moment around x-axis

The main girders and the transversal girders where modeled as line supports together with the end sections of the bridge. For the field marked in Figure 11 – above (between 27-36 m) patch loads where applied according to load model 1 as shown in Figure 12 - Showing the paths for witch the result is plotted.

For the case of a transversal oriented SSE deck the system is modelled without transversal girders; hence the force is transferred by the SSE deck to the main girders.

The whole length of the bridge is not taken into consideration.

3.2.4 Results from FE-analysis

The static analysis carried out for the two different orientations of the SSE showed that there was a large difference in the way the system carries the load. By applying an orientation of the SSE with the stiffer direction in the bridge longitudinal direction the load is carried in the length direction of the bridge with peak moments and shear forces over the transversal girders as a result. By applying a perpendicular orientation of the SSE the moment around the y-axis (transversal axis of the system) becomes smoother and without peaks as the main load carrying direction is transversal to the main girders.

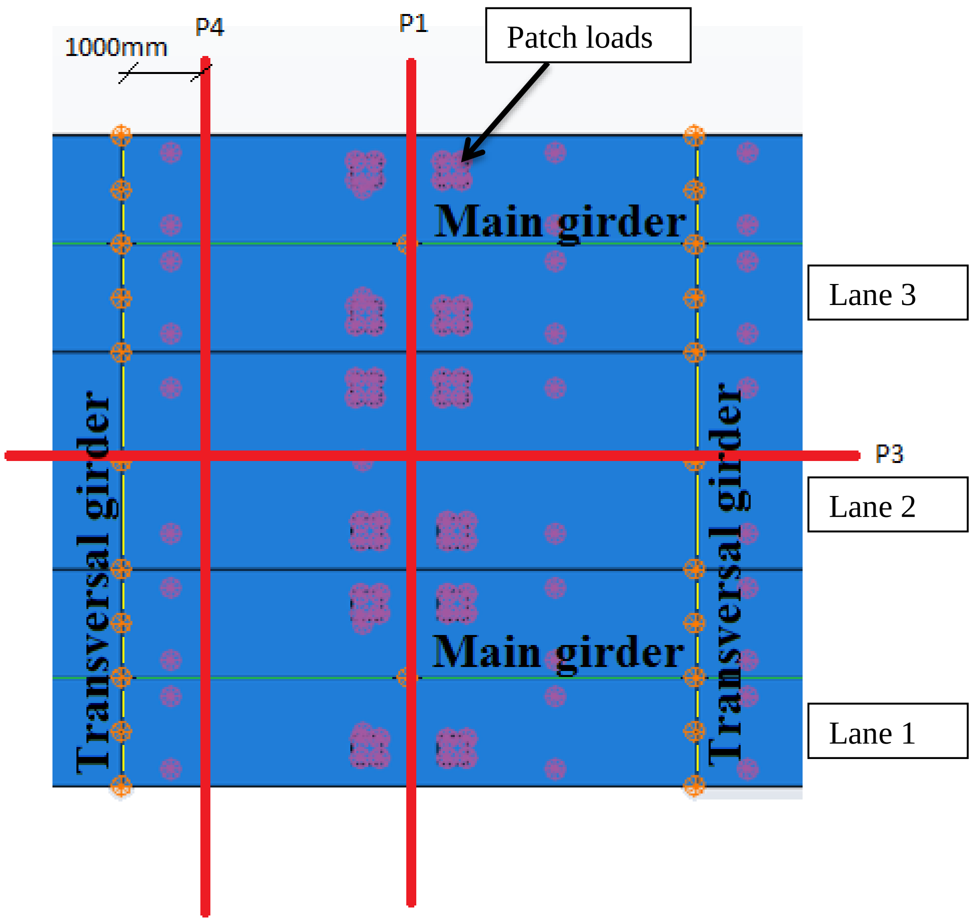


Figure 12 - Showing the paths for witch the result is plotted

All results presented below are normalized and plotted for the paths P1, P2 and P4 shown in Figure 13 where the x-direction is parallel to P3 and the y-direction is parallel to P1 and P4.

For the case where the SSE is oriented in the longitudinal direction, category 1, we get high sectional moments around the y-axis over the supports in the direction of the system. For the transversal orientation however the sectional moment around the y-axis is more uniform along the length of the system, see Figure 13 – Sectional moment around the y-axis along path P3.

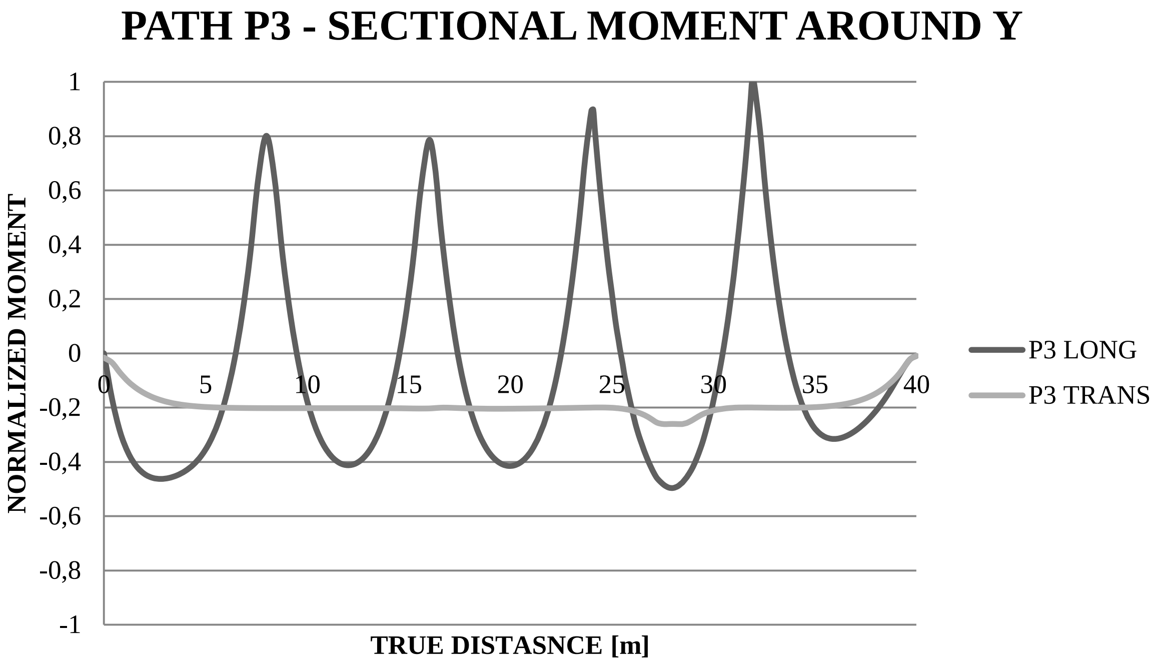


Figure 13 – Sectional moment around the y-axis along path P3

The load is carried mostly in the longitudinal direction for the SSE orientated in the bridge direction we get high shear forces near the transversal girders. For the SSE with transversal orientation we have no transversal girders which gives us a shear force without local peaks except from in the end spans, see Figure 14 – Sectional shear force in the x-direction along path P3.

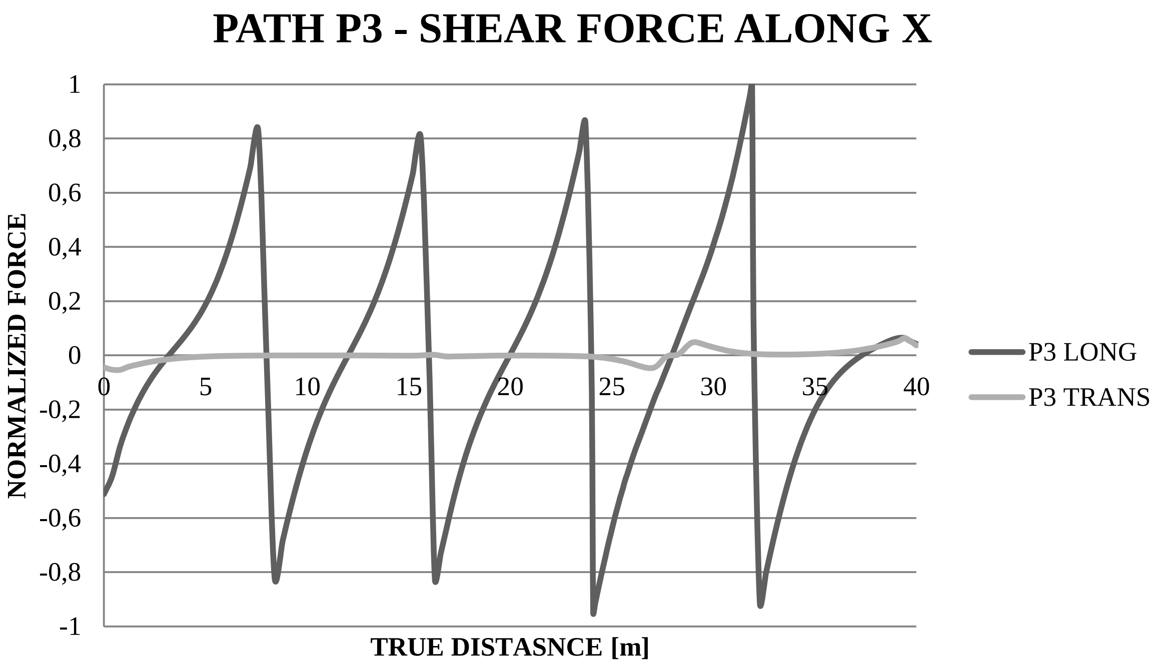


Figure 14 – Sectional shear force in the x-direction along path P3

The moment around the x-axis is dependent on the orientation of the SSE. For the SSE oriented in the longitudinal direction of the bridge there is less moment around the x-axis than for the SSE oriented in the transversal direction.

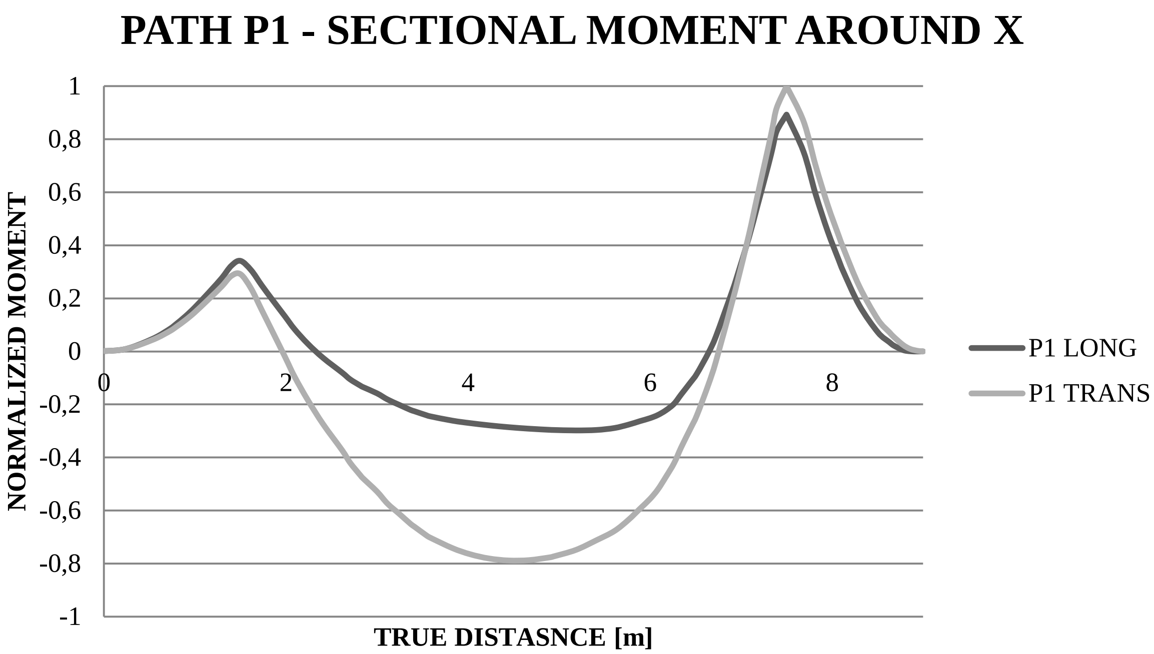


Figure 15 – Sectional moment around the x-axis along path P1

For the SSE used in the analysis the stiffness ratio between the x- and y-direction is almost 1, hence we have an almost isotropic deck. Therefor the moment and shear force distribution in the mid span looks similar to each other.

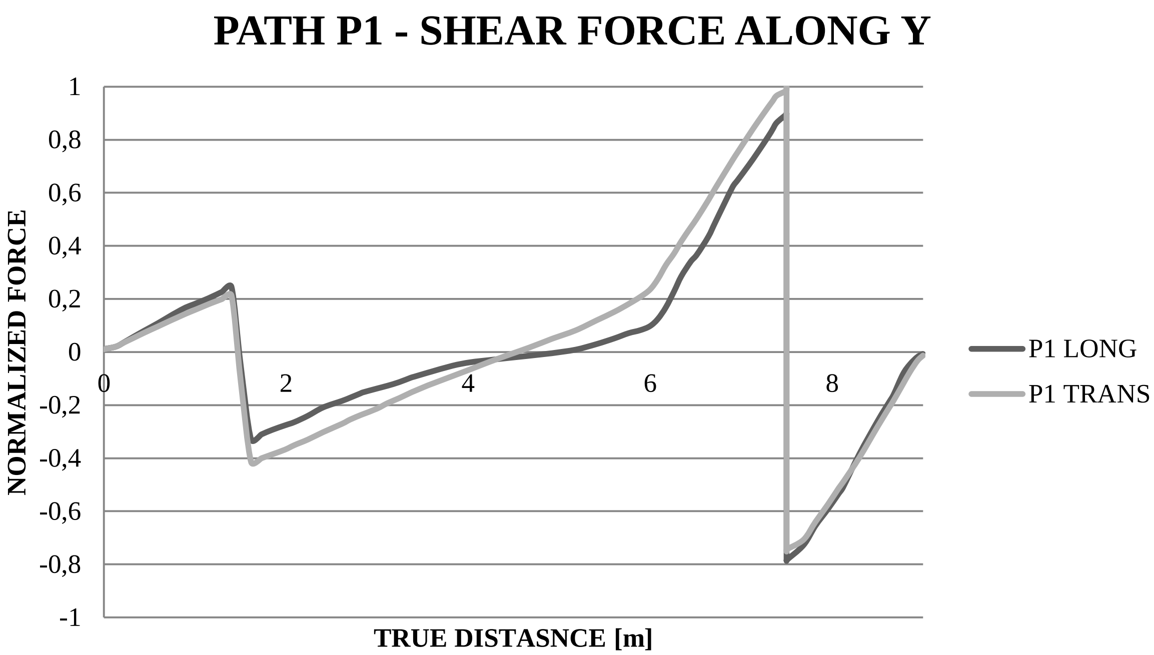


Figure 16 – Sectional shear force in the y-direction along path P1

3.3 Concept category 1: Longitudinal oriented SSE

Transversal joining of the elements must be done in a way that not significantly changes the stiffness of the bridge deck. The optimal solution would be to join the element edges together by butt welding the full sections together. However due to practical issues with access this is not possible.

The combination of shear force and bending moment in the cross-section makes the joint challenging. There are two principal positions of the joint;

- The joint is located in the field which will expose the joint to stresses from both bending moment and shear
- The joint is located above the transversal beams which will expose the joint to pure bending

If the shear force can be neglected the problem of joining the elements is narrowed down to that of taking care of the bending stress and normal forces. This can be done by placing the joints on transversal girders allowing the shear force to flow directly to the transverse girder.

From the FE-analysis the result shows that the longitudinal oriented SSE is carrying the load in the direction of the bridge to the transversal beams. Hence the force is transmitted along the x-axis to the transversal beams acting as a support for the SSE. The force is further transferred by the transversal beams to the main girders and further to the supports. Hence there is a need of transversal beams to utilize this load bearing system.

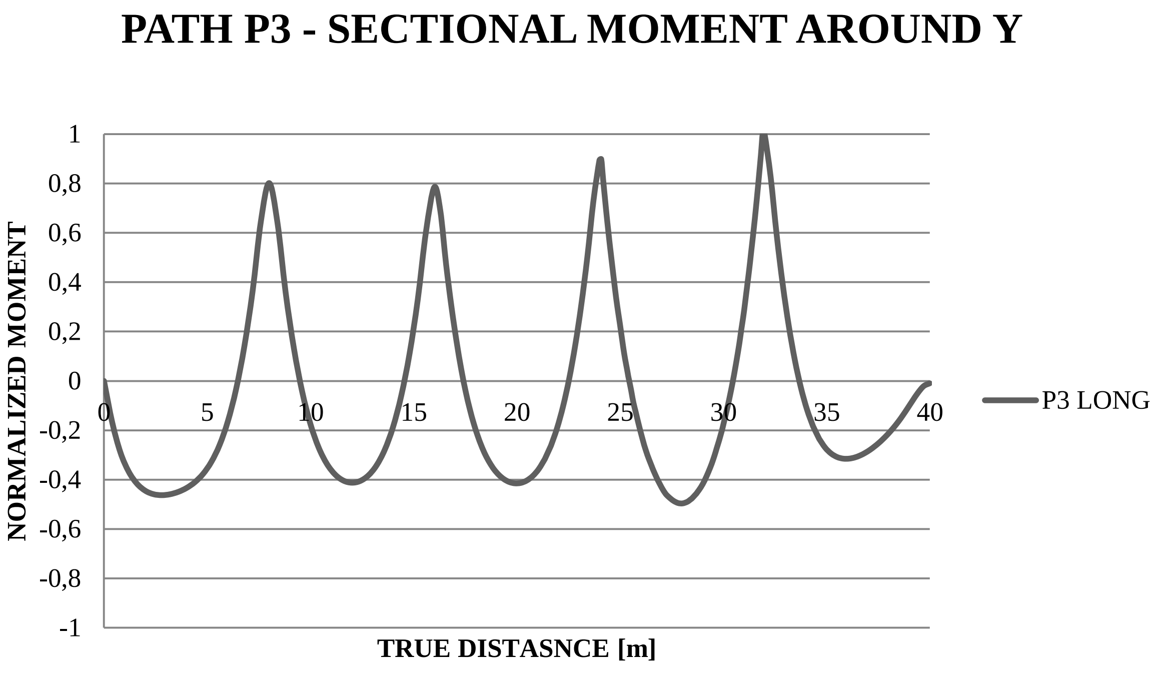


Figure 17 – Sectional moment around the y-axis along the length of the bridge

For a system of longitudinal oriented SSE the longitudinal joint (Joint B) will need to be designed to withstand the transversal sectional forces. In the mid-span the sectional shear force needed to be transferred is approximately the same as for the Category 2 concepts. The sectional moment however is less than for Category 2 concepts.

3.4 Concept category 2: Transversal oriented SSE

Longitudinal joints are the element to element joints between SSE running in the main direction of the SSE element. Independent of the system there will be longitudinal joints in the deck. These joints must be designed with a good fatigue durability as well as adequate moment and shear force capacity.

For the design purpose the joint must be at least as strong as the surrounding SSE elements. This can be achieved in a number of ways. However, the joint must be possible to manufacture both in-situ or in a factory depending on the choice of weld procedure and system design.

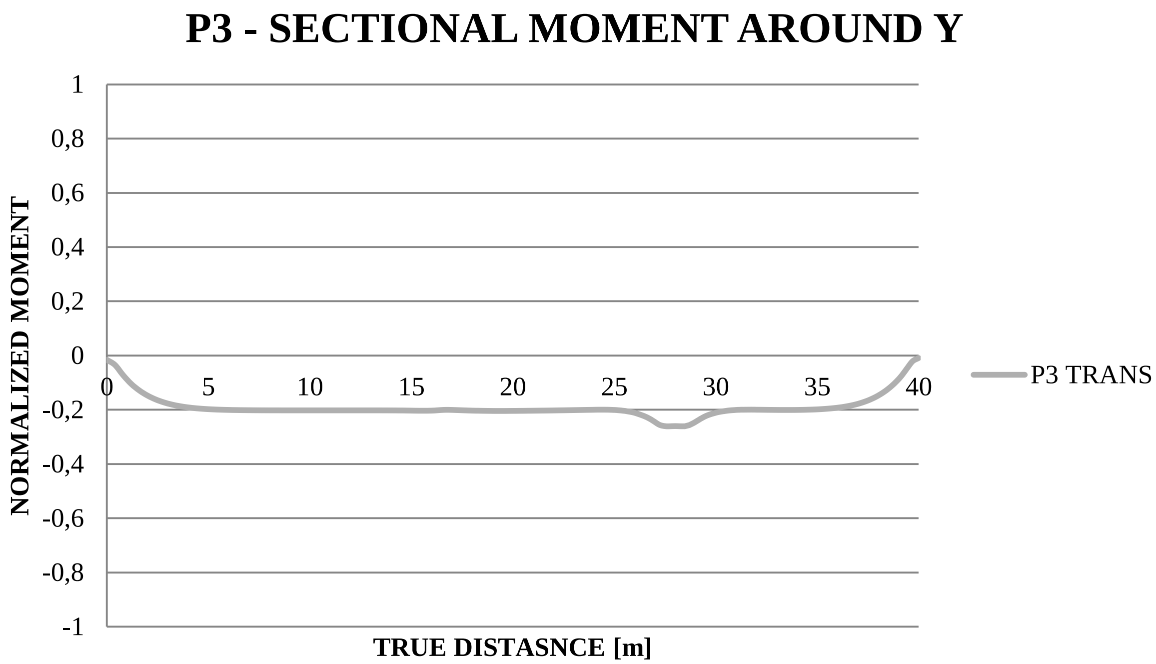


Figure 18 – Sectional moment around y-axis along the length of the bridge

Figure 18 shows the sectional moment distribution around the y-axis along the bridge length. By using a transverse oriented SSE the stiffness of the bridge deck is now higher perpendicular to the main girders. Hence the sectional moment around the y-axis along the bridge length will be small and the sectional moment around the x-axis perpendicular to the bridge length will be larger. The load bearing system can be described to transfer the loads applied on the SSE directly to the main girders and further to the supports. Hence the need of transversal girders for the purpose of creating a load path is superfluous.

For the Category 2 concepts the sectional forces in the longitudinal direction of the bridge is small. For bridge widths less than the maximum length of the SSE the need of transversal SSE joints (Joint A) is therefore not present.

The global bending stresses from the bridge cross-section will give rise to high compressive stresses in the top flange of the SSE. Hence the orientation the top flange is unstiffened with regard to local buckling the SSE can be ineffective acting as a flange in the system.

3.5 Amount of joints and cost evaluation

The needed amount of joints between SSE was derived and is presented in Table 8 – An example of a simple cost evaluation of a SSE bridge deck using simple calculations based on the geometry of the SSE and the bridge deck. By an approximation of the joint cost the calculation can be used for cost evaluation of the concepts. The evaluation is based only on assemble of SSE into a deck.

Table 8 – An example of a simple cost evaluation of a SSE bridge deck

Choice of system orientation		
Geometry SSE		
Width	3	[m]
Length	*9*	[m]
Geometry bridge		
Width	9	[m]
Length	65	[m]

	Long. Orient.	**Transv. Orient**	
Longitudinal joints	195	189	[m]
Transversal joints	63	0	[m]
Total length of joints	***258***	***189***	[m]

	Cost ratio	**Long. Orient.**	**transv. Orient**
Longitudinal joints	1	195	189
Transversal joints	2	126	0
		321	***189***
		100%	59%

4 ELEMENT TO ELEMENT JOINTS

The process of producing alternative element to element joints between SSE was carried out in two steps. First a quantitative process where alternatives where produced without no further constraints than the geometry. Hence the alternatives could be unconventional in terms of fastening method or shape.

By using the alternatives formed in the quantified process as a basis to a more qualitative evaluation the number of alternatives where decreased to eight promising ones.

4.1 Development of different alternatives

The forty-four alternatives shaped in the creative process were narrowed down to eight promising alternatives. This was done by rejecting alternative with obvious large obstacles as high cost, low fatigue strength and manufacturing issue’s in collaboration with associated Professor Mohammad Al-Emrani and MSc. Peter Nilsson.

In order to find the most suitable alternatives all joints where evaluated with respect to strength, stiffness and production. The alternatives where assigned a score based on the strength of the joint where with regard to moment capacity, shear capacity and fatigue endurance together with the manufacturability, sustainability and cost.

4.2 Qualitatively alternatives

From the forty-four alternatives there was ten alternatives left after the first evaluation session. Out of these eight there where three alternatives for joining of SSE in the longitudinal direction: Joint B. And five alternatives for joining of SSE in the transversal direction: Joint A.

4.2.1 Transversal connections: Joint A

The transversal connection is in the perpendicular direction to the corrugated steel core ribs.

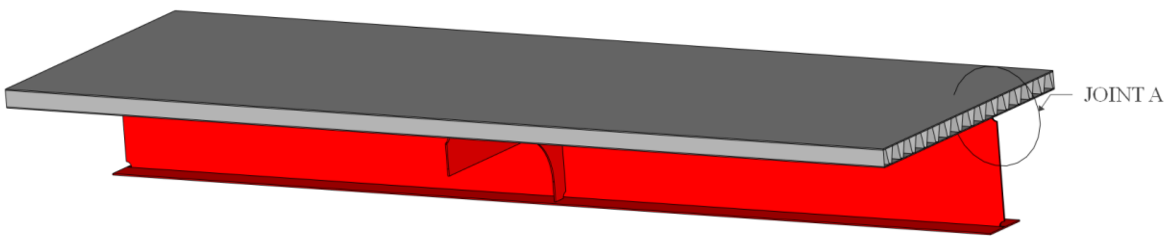


Figure 19 – Principal figure showing a transversal joint (Joint A) in a bridge system

The special case of a bridge deck consisting of only joint type A can be defined for both transversal and longitudinal orientation of the SSE.

The longitudinal orientation of the SSE is showed in Figure 19 – Principal figure showing a transversal joint (Joint A) in a bridge system. Governing dimensions are the dimensions possible to produce and transport. If the length of the SSE is shortened to less than 3500 mm, a section of SSE with a total width of about 26000 mm can be assembled in the factory. This will yield an in-situ joint of type A for each 3500 mm of the bride length and no in-situ joints of type B.

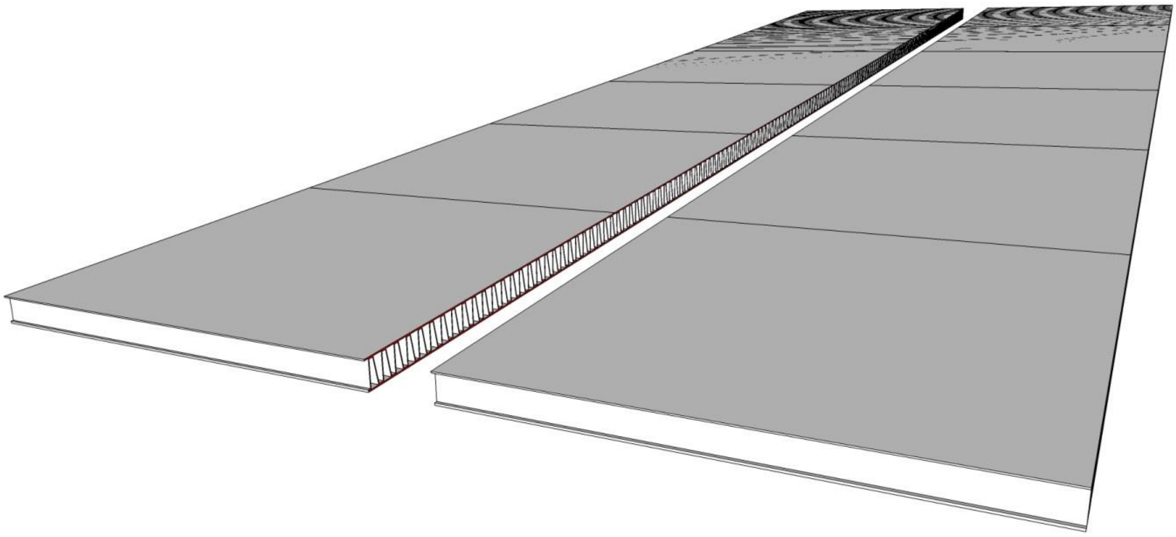


Figure 20 – Principal showing how a bridge deck can be built up using only joint type A

If the SSE is produced as long as possible the total width of the bridge deck in order not to get any joints of type B will be, accordingly to the reasoning above and figure 22, 3100-3500 mm. And the distance between the transversal beams can be prolonged to a distance of choice.

In Table 9 the joints are presented based on the meter weld / meter joint and fatigue category. The fatigue category is dependent on if the weld is tested with a no destructive testing (NDT) method. Note that for alternative A1 there are bolted connections as well as welds.

Table 9 – Meter weld and fatigue category for alternatives A

	A1	A2	A3	A4	A5
Meter weld / Meter joint [m/m]	2	3	3	4	2
Fatigue category, top plate, with/without NDT [MPa]	36/71	71	36/71	36/71	71
Fatigue category, bottom plate, with/without NDT [MPa]	-	36	36	36	71

4.2.1.1 Alternative A1

The connection is based on a girder system with no top flanges on the main or transversal girders. The transvers connection is located above the transversal girders.

The SSE is provided with L-steel used for bolting the SSE to the transversal girders. The SSE is also to be bolted together in the top of the elements before a cover plate is attached and the section is closed.

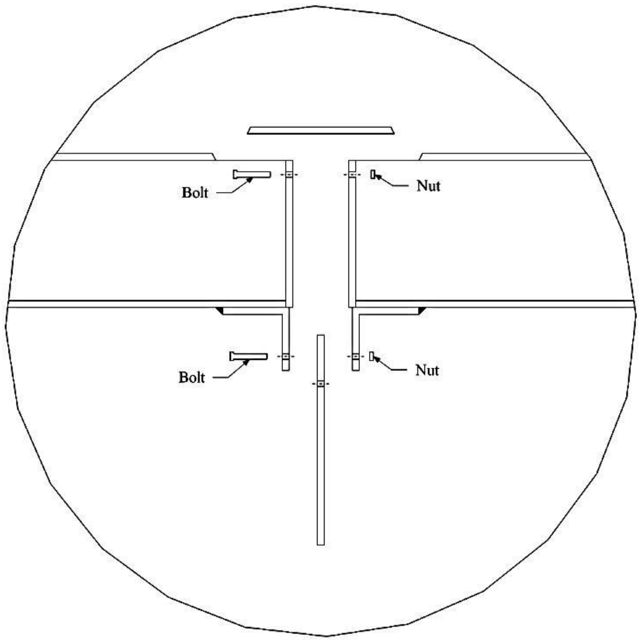


Figure 21 - Principal figure showing alternative A1

In order to be able to assemble the system there is a need of drilled holes for the bolting. The drilling procedure can be carried out either in-situ or in the factory. Interaction between the main girder and overlaying SSE is achieved by neck welding. For this concept the SSE is spliced above the transversal beams. By using primary and secondary girders without top flanges the stability of the webs could be a problem. The unstiffened web will be prone to buckle before the SSE is assembled to the system. The L-profile needs to be welded to the transversal girder to air tighten the SSE deck.

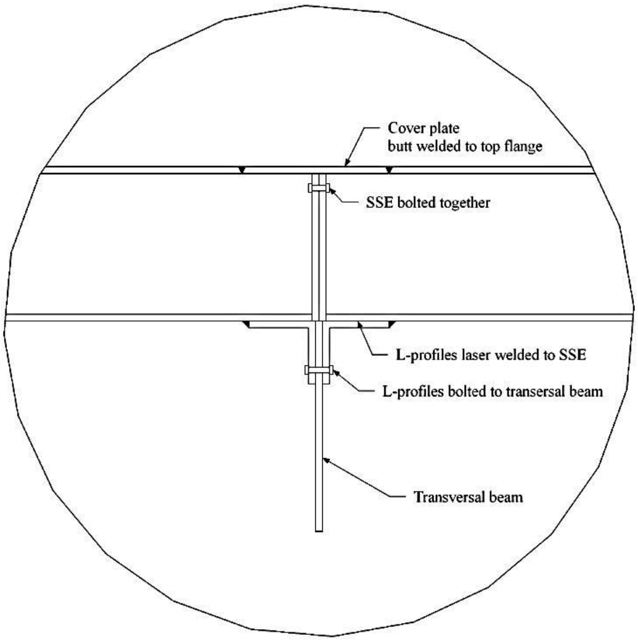


Figure 22 – Principle figure showing alternative A1 assembled

4.2.1.2 Alternative A2

The joining of SSE elements is carried out above the transversal girder in the system. The elements are lifted in place on site and are welded according to Figure 21 - Principal figure showing alternative A1. The SSE is attached to the main girder by fillet welding along the bridge.

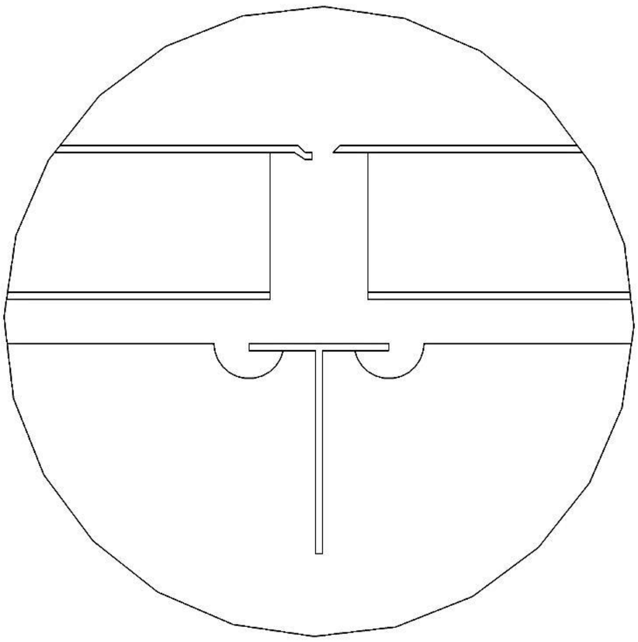


Figure 23 - Principal figure showing alternative A2

The top flange of the SSE is bent on one short side to act as a backing bar for the butt weld. In the bottom of the SSE the elements are fillet welded to the top flange of the transversal beam. Hence there is a high demand on tolerance and need of precision.

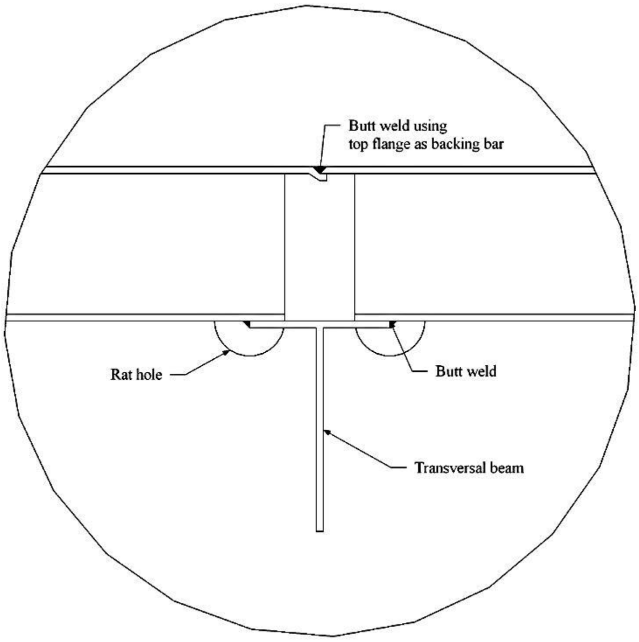


Figure 24 – Principle figure showing alternative A2 assembled

The unstiffened web of the main girder will be prone to buckle during lifting and handling on site. For point loading right above the short side of the SSE the corrugated core will be exposed to high shear force. The free edge could be prone to buckle and will possibly have to be stiffened. By using open cross-sections of the SSE a full air tightness test can be carried out for the whole bridge deck at once. The girders and SSE are prefabricated and transported to the construction site. Girders and floor beams are joint together and the SSE is assembled to the system.

4.2.1.3 Alternative A3

Before assemble of the SSE the web of the main girder is unstiffened and sensitive to impacts and distortions. The process of lifting the SSE into place needs to be done without damaging the main girders.

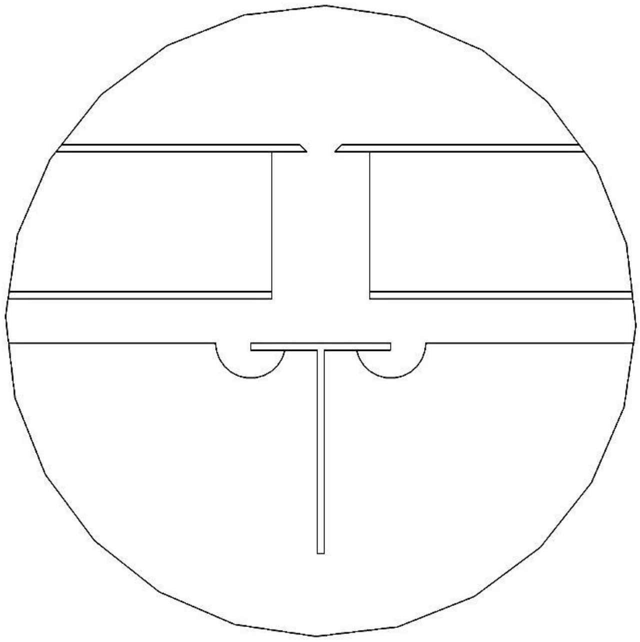


Figure 25 - Principal figure showing alternative A3

By using open cross-sections of the SSE a full air tightness test can be carried out for the whole bridge deck at once. For patch loading directly over the joint the free edge of the steel core will be exposed to high vertical force and could be prone to buckle.

A proposed assembly plan could be that the girders and SSE are prefabricated and transported to the construction site. Girders and floor beams are joint together and the SSE is assembled to the system.

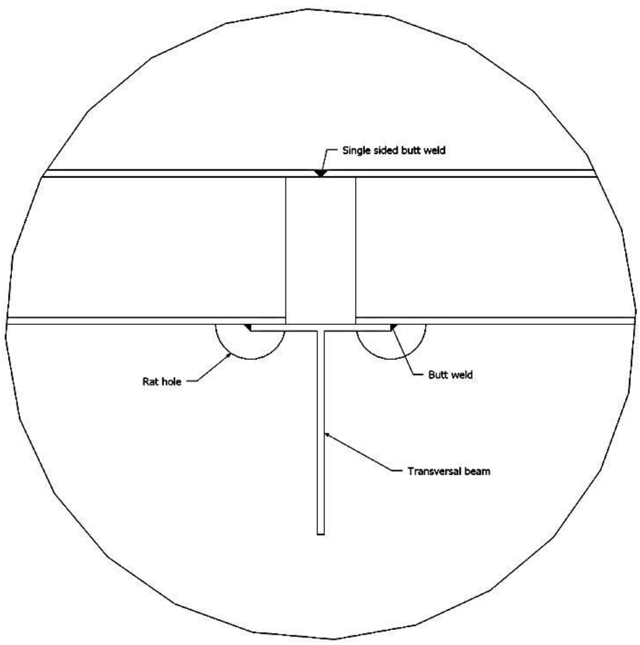


Figure 26 – Principle figure showing alternative A3 assembled

The alternative A3 is based on the principle of joining the elements together above a transversal beam. The elements are lifted into place on the construction site and the welded to the top flange of the transversal beam. In the top the elements are butt welded together by a single sided butt weld. And the SSE is connected to the main girder by longitudinal neck welding. The fitting procedure is simple and straight forward and the number of joints are rather low.

4.2.1.4 Alternative A4

The joining of SSE is carried out above a transversal girder. The girders can be prefabricated as a system and assembled together with the SSE on site.

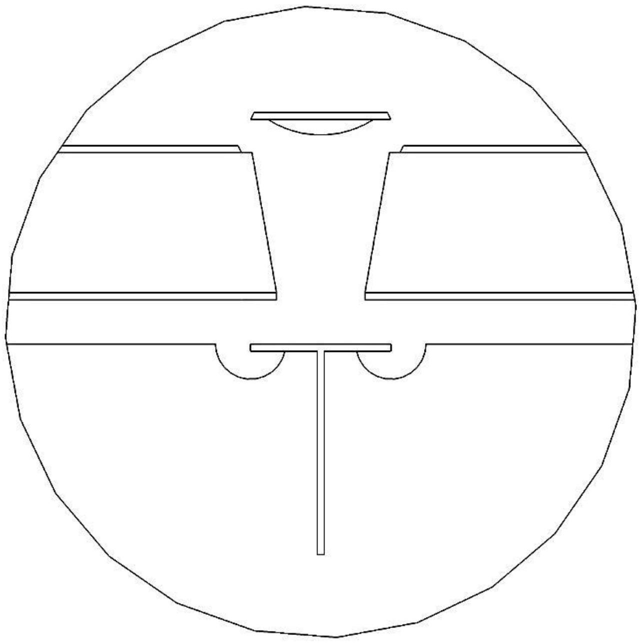


Figure 27 - Principal figure showing alternative A4

After that the fillet welds inside of the sections are done the cover plate is welded in place. The whole process calls for a lot of welding and each joint will therefore be both time and cost consuming. Also the neck welds between the main girders and the overlaying SSE must be carried out on the construction site.

The cover plate must be rigid enough to withstand the membrane stresses from global bending and axial forces. The cover plate also needs to be able to handle the patch loading occurring directly over the joint. This could be achieved by stiffening of the plate or thickening of the same. Also the free edges of the steel core need to be designed to handle the patch loading.

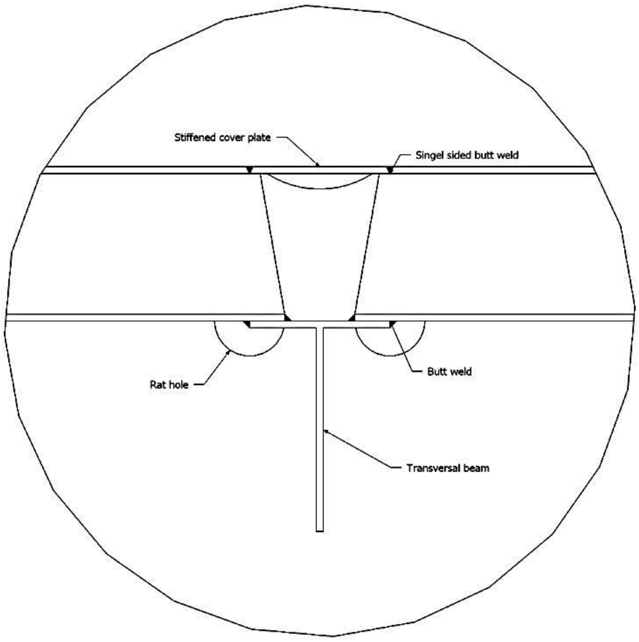


Figure 28 – Principal figure showing alternative A4 assembled

4.2.1.5 Alternative A5

The joint is carried out away from the transversal beam and the exact location can be chosen by the designer. The cross-section can be prefabricated including the SSE to reduce the in-situ welding.

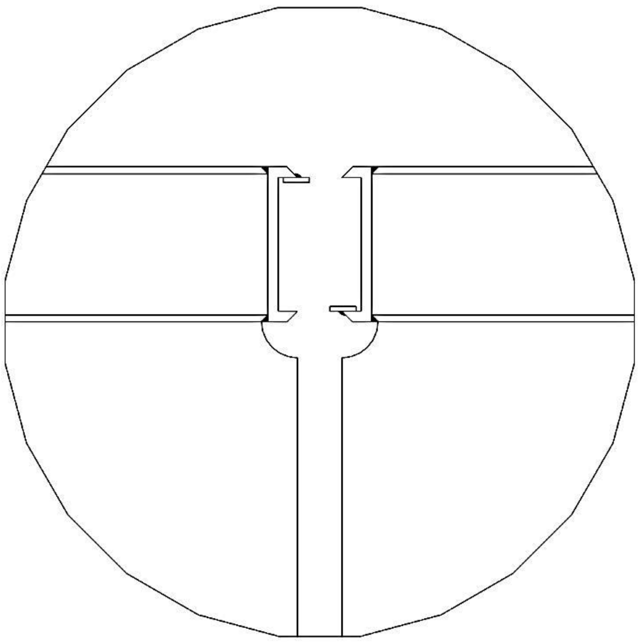


Figure 29 - Principal figure showing alternative A5

The SSE is prepared with a U-profile in the short sides in the factory. The profile is attached by laser welding to the steel core to gain full interaction. To ease the assembly and the single sided butt welding the U-profiles are prepared with a backing bar fillet weld from the root side.

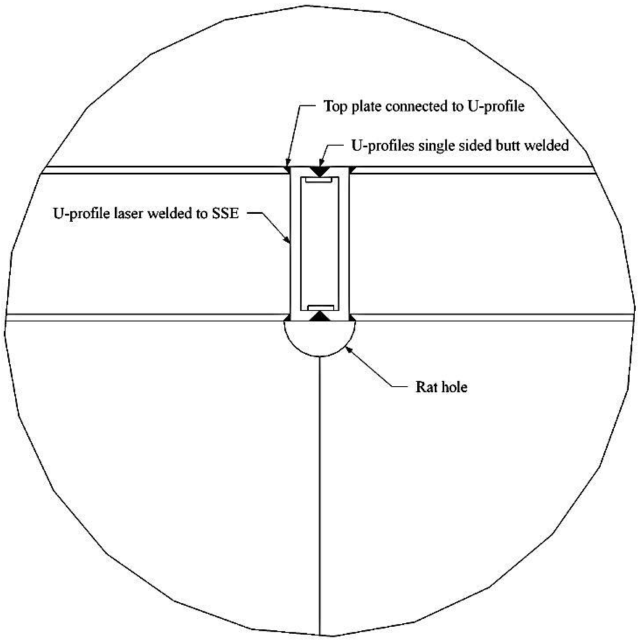


Figure 30 – Principal figure showing alternative A5 assembled

The joining of sections on site is carried out by means of two butt welds joining the U-profiles and the main and transversal girders are spliced in a conventional way. The joint together U-profiles will act as a rigid frame under Vierendeel action where the shear deformation will give rise to a moment in the top and the bottom flanges. By using a “splicing element” the joint can be designed to withstand the load effects in the section without having to change the dimensions of the top and bottom plates in the SSE.

In order to make air tightness testing on site possible the SSE needs to be prepared with holes to make it possible for air to flow throughout the whole deck.

4.2.2 Longitudinal connections: Joint B

The longitudinal joint is in the direction of the corrugated steel core ribs.

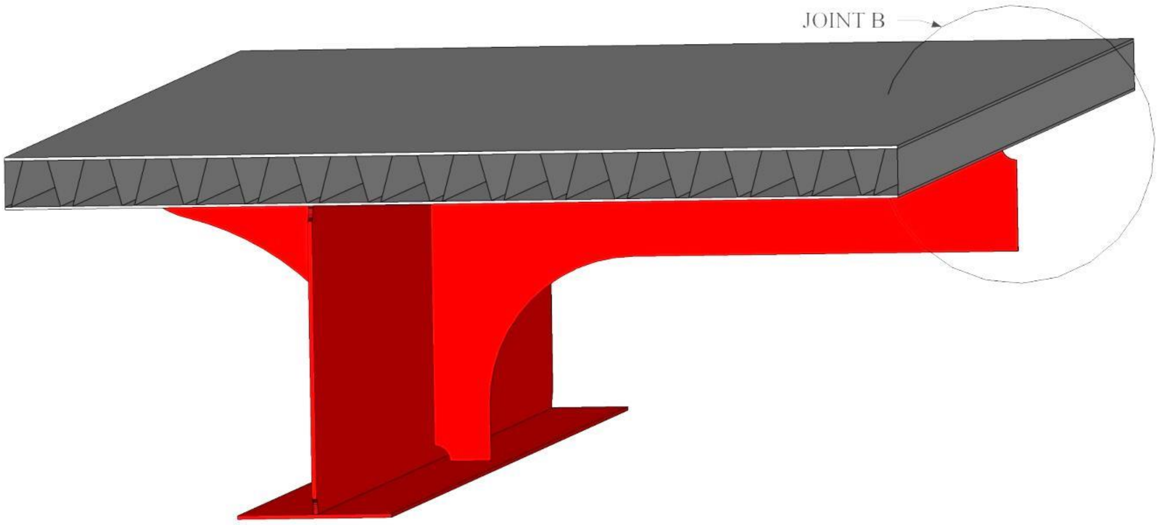


Figure 31 - Principal figure showing a longitudinal joint (Joint B) in a bridge system

For the special case of producing a bridge deck consisting of only type B the bridge deck configuration can be built up either by SSE elements oriented in the longitudinal direction or in the transversal direction.

For the case of longitudinal oriented SSE the length of the element possible to transport is governing for the bridge deck length. For the case of transversal oriented SSE the bridge deck can be built without any geometrical constrains on the bridge length. However the bridge width is constraint to be less than the maximal possible length of element to transport.

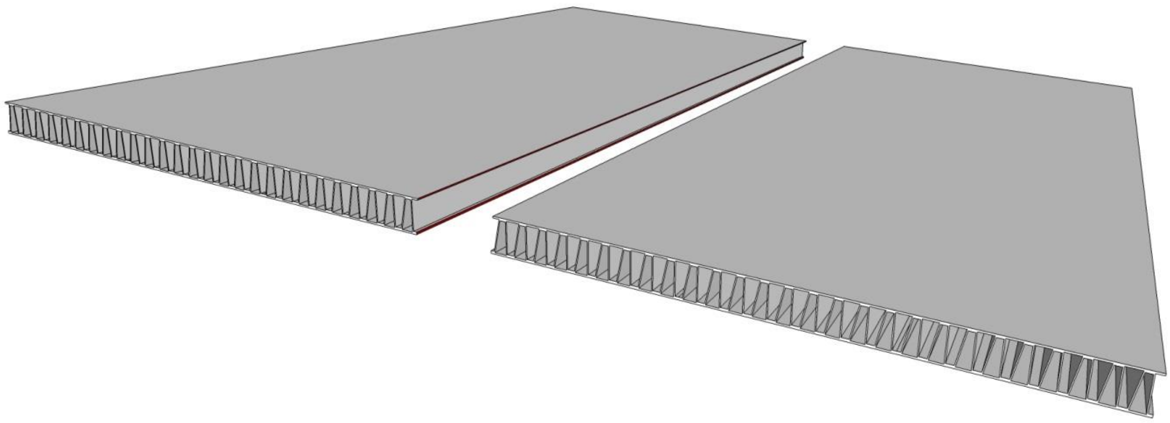


Figure 32 - Principal showing how a bridge deck can be built up using only joint type B

In the table below joints are presented based on the meter weld / meter joint and fatigue category.

Table 10 - Meter weld and fatigue category for alternatives B

	B1	B2	B3
Meter weld / Meter joint [m/m]	2	3	2
Fatigue category, top plate, with/without NDT [MPa]	71	71	36/71
Fatigue category, bottom plate, with/without NDT [MPa]	36/71	36/71	36/71

4.2.2.1 Alternative B1

The SSE is joined by butt welding together the top plates and the bottom plates. The corrugated steel core acts as a backing bar to the butt weld in the top plate and in the bottom plate the bottom plates and the corrugated steel cores are single sided butt welded together.

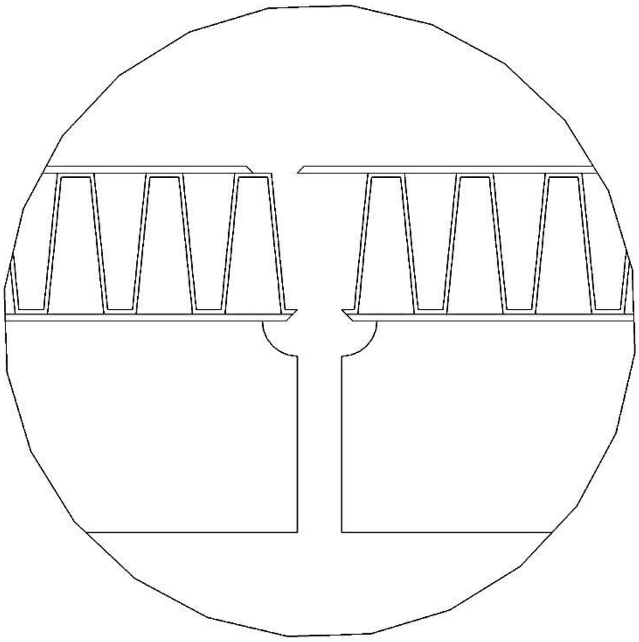


Figure 33 – Principal figure showing alternative B1

The joint calls for two longitudinal single sided butt welds to be carried out. The butt welds are shifted so that they are not in the same section.

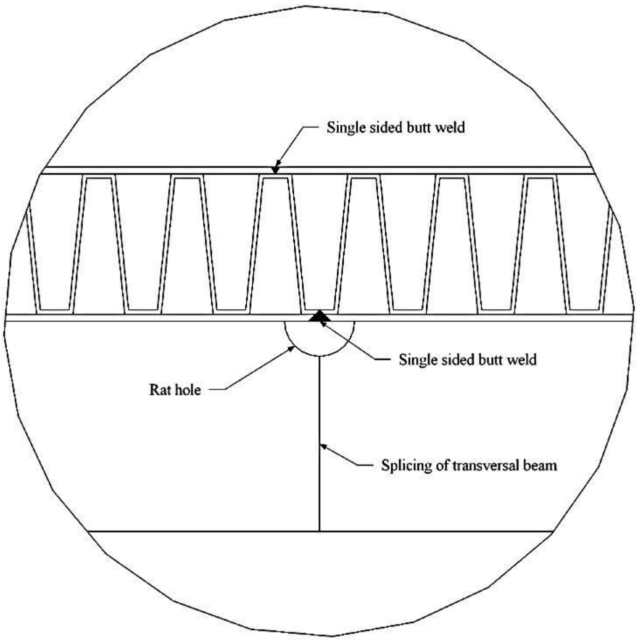


Figure 34 – Principal figure showing alternative B1 assembled

4.2.2.2 Alternative B2

The bottom plates are joint together using a double sided butt weld. Afterwards a cover plate is applied and single sided butt welded to the top plates to close the section.

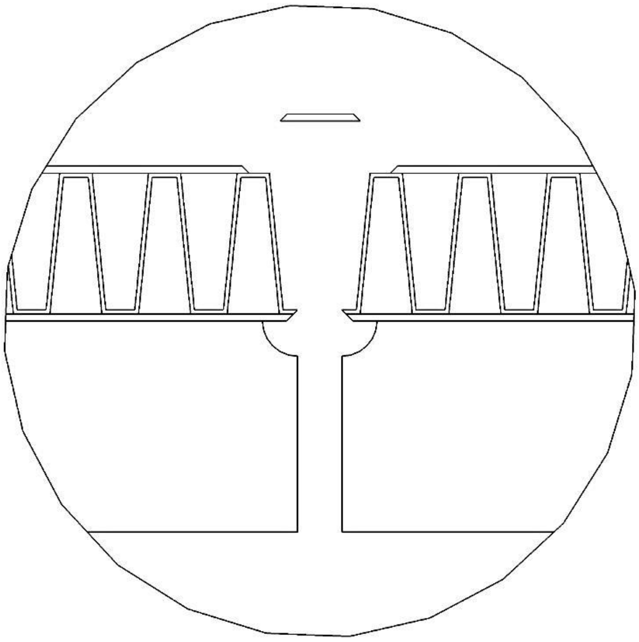


Figure 35 – Principal figure showing alternative B2

This joint demands one more part to be assembled and also one more weld in the production sequence.

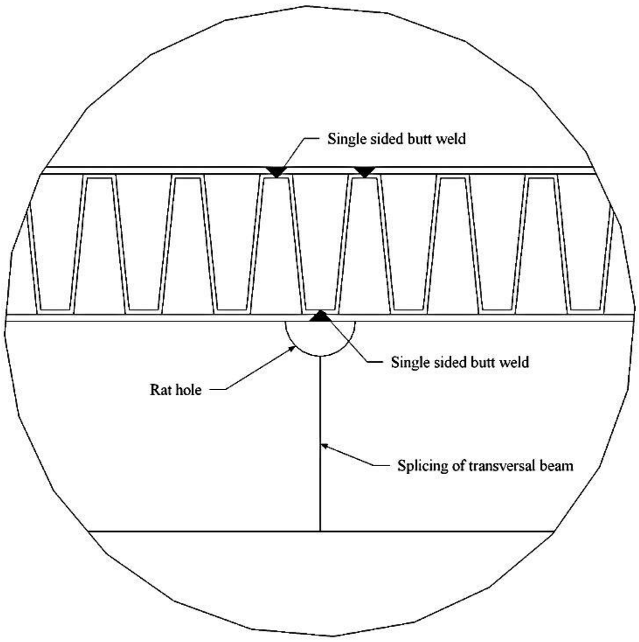


Figure 36 - Principal figure showing alternative B2 assembled

4.2.2.3 Alternative B3

The longitudinal joining of two SSE is carried out using single sided butt weld to join the top plates and the bottom plates. Hence this alternative is straight forward to produce in the steel shop.

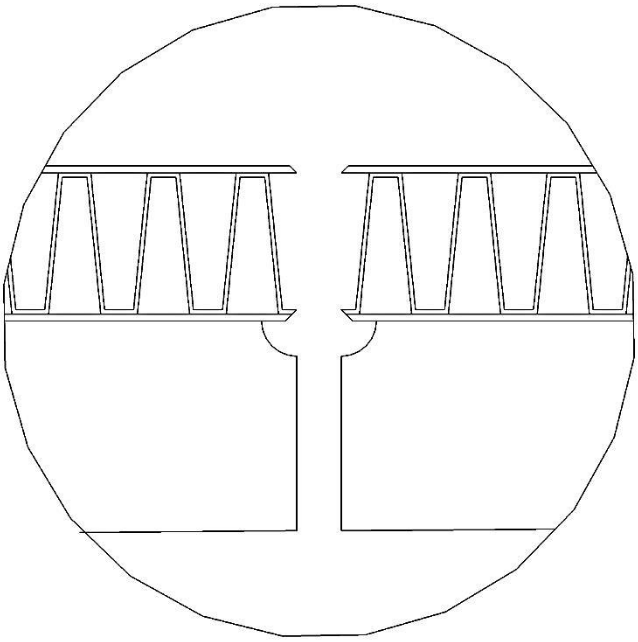


Figure 37 – Principal figure showing alternative B3

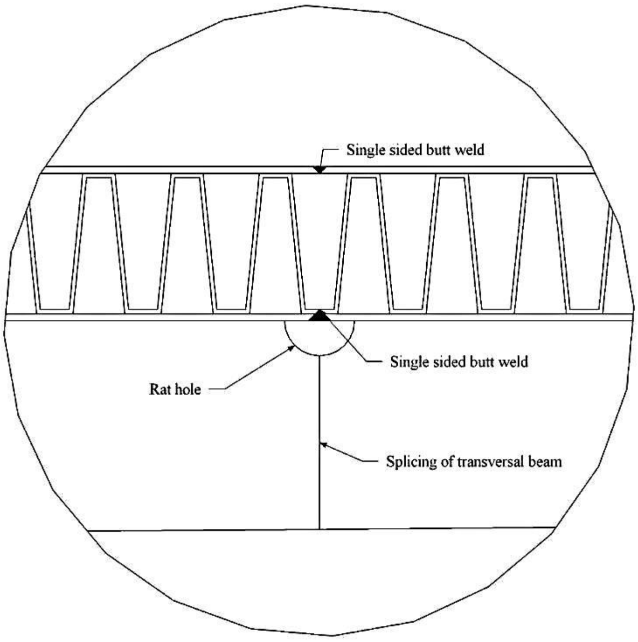


Figure 38 - Principal figure showing alternative B3 assembled

5 EVALUATION OF ELEMENT TO ELEMENT JOINTS

The evaluation of element to element joints was based on the DFMA methodology presented in the literature study. The conceptual joints evaluated in this chapter are presented in chapter 4.

Evaluation of the concepts was conducted in cooperation with associate Professor Mohammad Al-Emrani and MSc. Peter Nilsson. Each alternative was given a score based on the score tables presented in the literature study.

5.1 Relative importance and evaluation matrices

By using the principle presented in the literature study the weighted client requirements can be transformed into design requirements and give the relative importance of each design criterion.

The design requirements used for the purpose of evaluation of the joints where defined as:

- Tolerances: The right tolerances
- Reduced number of parts in assembly: By reducing the number of parts to be assembled the risk of mistakes is reduced and the design procedure is simplified.
- Mistake-proof connection: The joints should be designed to fit only in on certain way to minimize the risk of mistakes in the joining.
- Minimize movement and rotation: To move and rotate parts is non-value creating actions. This should be reduced to keep the assemble process cost effective and rapid.
- Safety during construction: The pars should be designed to be safe for workers and other materials. Eg. Sharp edges should be avoided.
- Standardization: Less inventory cost and less additional evaluation and experimentation is needed. By standardization the cost can be reduced.
- Avoid time-consuming joints: The difficulty of joints

Table 11 – Mapping of client requirements into design requirements

Client requirements	Weight [client]	**Design requirements**					
		Tolerance	Reduced number of parts in assembly	Mistake-proof design	Minimize movement and	Standardization	Avoid time consuming joints
Quick bridge erection	8	3	2	3	3	3	3
Total cost	8	2		2	2	3	2
Need of maintenance	6		1				
Ease of inspection	9		2			1	1
Quick repair/replace	9					1	2
Low noise and vibration	5	2	1				
Low energy and CO_2	5	1				2	
Safe	9	1		2	2	2	
Absolute importance		64	45	58	58	94	67
Relative importance		17%	12%	15%	15%	24%	17%

The evaluation matrix presented in Table 9 will be used to give the alternatives score based on the design requirements.

Table 12 – Evaluation of joint alternatives based on the relative importance of the design requirements

Design requirements	Relative importance	Joint concept					
		A1	A2	A3	A4	A5	
Tolerance	17%						
Reduced number of parts in assembly	12%						
Mistake-proof design	15%						
Minimize movement and rotation	15%						
Standardization	24%						
Avoid time consuming joints	17%						
Score		0	0	0	0	0	0

A score is given for each design requirement and the definition of the score is presented in Table 12.

Table 13 – Definition of score for evaluation of joint concepts

	Score definition	
Design requirements	**1**	**5**
Tolerance	Very low tolerance	High or irrelevant tolerance
Reduced number of parts in assembly	Many parts to be assembled	One part only
Mistake-proof design	Can be assembled in different ways	One-way assembly
Minimize movement and rotation	A lot of movement and rotation in assembly	No movement and rotation
Standardization	Not standardized at all	Fully standardized
Avoid time consuming joints	Many fasteners	No fasteners

5.2 Evaluation of transversal joints

For the transversal joints, alternatives A1-A5, the result is presented in Table 14. The winning alternative, as presented in Table 15, is alternative A5.

Table 14 – Score board for evaluation of alternatives A

	A1		A2		A3		A4		A5	
Tolerance	Very low tolerance due to the bolted connection. The pre drilled holes must be fitted accurately during assembly	1	High tolerance. The bent top flange acting as a backing bar which makes s the weld joining of the top flanges less tolerance sensitive.	4	Similar to A2, but without the bent top flange. Hence the tolerance is lower than for A2.	3	High tolerance.	4	High tolerance due to the backing bars in the U-profiles. The backing bars makes the weld less tolerance sensitivity.	4
Reduced number of parts in assembly	Many ingoing parts	1	Only steel sandwich elements. Few parts.	4	Only steel sandwich elements. Few parts.	4	Steel sandwich elements and a cover plate.	2	Only steel sandwich elements. Few parts.	3
Mistake-proof design	Complex connection with many ingoing parts.	1	Sensitive for distortion.	2	Sensitive for distortion	2	More parts than just the steel sandwich elements.	3	Can be designed to only fit in one way.	4
Minimize movement and rotation	Must be kept in place during assembly. High need of crane handling.	1	Can be lifted in place and adjusted for god fitting.	3	Can be lifted in place an adjusted for god fitting.	3	More parts that need to be moved into place	2	Must be kept in line during assembly. Need of crane or support.	4
Standardization	Hard to standardize	3	Could be standardized	4	No special features	4	Special stiffened cover plate	2	Could be standardized	4
Avoid time consuming joints	Connection containing many joints and many of them are time consuming.	1	Straight forward butt welding (one with support)	3	Straight forward butt welding	3	More welds. Intermittent support under butt welds connecting the cover plate.	2	Butt welding with supporting backing bars.	4

Table 15 – Scoring with relative importance

Design requirements	Relative importance	**Joint concept**				
		A1	A2	A3	A4	A5
Tolerance	17%	1	4	3	4	4
Reduced number of parts in assembly	12%	1	4	4	2	3
Mistake-proof design	15%	1	2	2	3	3
Minimize movement and rotation	15%	1	3	3	2	4
Standardization	24%	3	4	4	2	4
Avoid time consuming joints	17%	1	3	3	2	4
Score		1,5	3,4	3,2	2,5	3,7

5.3 Evaluation of longitudinal joints

For the longitudinal joints, alternative B1-B3, the result is presented in Table 16. The winning alternative, as presented in Table 17, is alternative B1.

Table 16 – Score board for evaluation of alternatives B

	B1		B2		B3	
Tolerance	Good tolerance	**4**	Good tolerance	**4**	The top flange is sensitive to distortion.	**2**
Reduced number of parts in assembly	One weld in the top and one weld in the bottom.	**3**	Two welds in the top and one weld in the bottom.	**2**	One weld in the top and one weld in the bottom.	**3**
Mistake-proof design	Can only be fitted in one way.	**4**	Many ingoing parts.	**2**	Risk of assembled upside-down.	**2**
Minimize movement and rotation	Easy movement with low need of rotation.	**3**	More parts to transport and handled.	**1**	Easy movement with low need of rotation.	**3**
Standardization	Could be standardized.	**3**	More parts, however all parts could be standardized.	**2**	Could be standardized.	**3**
Avoid time consuming joints	Straight forward to weld.	**4**	Straight forward to weld.	**4**	Straight forward to weld.	**B**

Table 17 - Scoring with relative importance

Design requirements	Relative importance	**Joint concept**		
		B1	B2	B3
Tolerance	17%	4	4	2
Reduced number of parts in assembly	12%	3	2	3
Mistake-proof design	15%	4	2	2
Minimize movement and rotation	15%	3	1	3
Standardization	24%	1	4	3
Avoid time consuming joints	17%	4	4	4
Score		3,0	3,0	2,9

6 Discussion

The task of finding a good joint solution for steel core sandwich elements has been proven to be extended beyond sketching and calculating stiffness and strength. There is more to the problem than just making the solution strong enough for its structural integrity. The problem at hand come to be more about the possibility to produce the corrugated core steel elements, transport them to the construction site and assemble them. And it is quite reasonable to have this approach since there is no point of being able to produce a bridge on the construction site if one cannot manufacture and transport the parts there.

The element to element joints will behave differently depending on the conceptual system of the bridge and also depending on the orientation of the SSE and distance between transversal girders. In a way the problem at hand has grown throughout the process to be about summary of all prerequisites and information to be able to make a valid evaluation in further studies.

In the process of investigating the element to element joints of corrugated core steel sandwich elements the reasoning about designing bridges with the deck oriented transversal to the length of the bridge come up. Further studies needs to be carried out, but by doing this the need of transversal beams for transmitting the load to the main girders is reduced.

7 Conclusions

The conclusions that can be drawn from this was that the work with developing the connections is long from finished and further studies needs to be conducted to come up with production processes for promising joint solutions. Another conclusion is that the SSE is highly dependent on the geometry and possibilities of transportation which yields well defined boundary conditions for the system of choice when designing a two girder steel bridge with SSE deck.

By choosing either a longitudinal oriented SSE or a transversal oriented SSE the bride deck can be designed for only one type of in-situ joints. The decisive factor for the deck geometry is then the transportation. The SSE elements must be possible to transport to the construction site, hence the biggest single element can have the dimensions ~3500x26000mm^2.

From the evaluation carried out in this thesis can be drawn some further conclusions. We see that the most promising alternatives are those with few ingoing parts to be assembled on the construction site and where the assemble process is easy and mistake-proof. This also means that the most promising solutions hold good conditions for prefabrication. However, the evaluation strategy has not been proven to be the best there is and for different type of projects the ingoing evaluation criteria should be adapted to the specific requirements of the project.

7.1 Recommended further studies

This report has been focusing on the concepts and different types of joints. A minor evaluation has been carried out to find a joint solution. However, the evaluation process has mostly focused on the possibilities of production, maintenance and in some manner cost. Further studies should be carried out where the joints are evaluated more thoroughly and analyzed by using numerical models both for the local parts but also in the global system with surrounding SSE.

It is further recommended to involve the industry in some manner. A bridge constructor and a manufacturer of SSE should be involved and allowed to tell their opinion so that all aspects of the build are covered.

The SSE deck can be used in both the longitudinal and the transversal orientation of the bridge. Further studies should be carried out with respect to the strength of the SSE depending on the orientation of the deck.

A study should be conducted to investigate for which cases it could be possible to prefabricate the whole bridge and specifying a production process for these cases. By special arrangements in the handling and transport this could probably cover a major part of the short and medium span bridges built. The result should tell whether it is advantageously or not to arrange with special transportations to be able to prefabricate the whole structure.

8 BIBLIOGRAPHY

Abbott, S. P. et al., 2007. *Automated laser welded high performance steel sandwich bridge deck development,* Maine: PLSystems.

AISI, 2015. *http://www.steel.org/.* [Online] Available at: https://www.steel.org/SMDISteel_org/Web%20Root/Construction/Bridges/Short%20Span%20Steel%20Bridges.aspx
[Accessed 23 06 2015].

Alwan, U. & Järve, D., 2012. *New Concept for Industrial Bridge Construction,* Göteborg: Chalmers university of technology.

BCSA, 2009. *BCSA Guide to the Erection of Steel Bridges,* London: The British Constructional Steelwork Association Ltd.

Beneus, E. & Koc, I., 2014. *Innovative road bridges with steel sandwich decks,* Göteborg: Chalmers university of technology.

Brian, M. V., 2011. Hybrid laser arc welding. In: *ASM Handbook; Volume 6A, Welding fundamentals and processes.* s.l.:s.n., pp. 321-328.

Bright, S. R. & Smith, J. W., 2004. Fatigue performance of laser-welded steel bridge decks. *The Structural Engineer,* pp. 31-39.

Bright, S. R. & Smith, J. W., 2007. A new design for steel bridge decks using laser fabrication. *The Structural Engineer,* pp. 49-57.

Chang, W.-S., Ventsel, E., Krauthammer, T. & John, J., 2005. Bending behavoir of corrugated-core sandwich plates. *Composite structures,* pp. 81-89.

Dackman, D. & Ek, W., 2015. *Steel sandwich decks in medium span bridges,* Göteborg: Chalmers university of technology.

Kalyun, M. & Wodajo, T., 2012. *Application of a Design Method for Manufacture and Assembley: Flexible Assebly Methods and their Evaluation of the Construction of Bridges,* Göteborg: Chalmers University of Technology.

Kisch, B. & Langefors, P., 2005. *Incremental launching versus scaffolding for construction of prestressed concrete bridges,* Göteborg: Chalmers university of technology.

Kujala, P. & Klanac, A., 2005. *Steel sandwich panels in marine applications,* Espoo, Finlan: Helsinki university of technology.

Mara, V. & Kliger, R., 2015. An approach for the development of connections between FRP bridge decks.

SANDCORE, 2005. *Best practice guide for sandwich structures in marine application,* s.l.: s.n.

SS-EN 1991-2, 2003. *Eurocode 1: Actions on structure - Part 2: traffic load on bridges,* s.l.: s.n.

Stålbyggnadsinstitutet, 2014. *http://sbi.se.* [Online] Available at: http://sbi.se/om-stal/brobyggnad
[Accessed 29 06 2015].

Trafikverket, 2011. *TRVK Bro 11,* s.l.: Trafikverket.

Trafikverket, 2013. *Trafikverket: Transport av odelbar last utan dispens.* [Online] Available at: http://www.trafikverket.se/Foretag/Trafikera-och-transportera/Trafikera-vag/Transportdispens/Transport-av-odelbar-last-utan-dispens/
[Accessed 24 08 2015].

Trafikverket, 2014. *http://www.trafikverket.se.* [Online] Available at: http://www.trafikverket.se/en/startpage/Operations/Operations-road/port-exemption-for-abnormal-road-transports/Transport-of-indivisible-load-without-exemption/
[Accessed 23 06 2015].

Transportstyrelsen, 2010. *TSFS 2010:141*, s.l.: s.n.

Transportstyrelsen, 2010. *TSFS 2010:142*, s.l.: s.n.

Transportstyrelsen, n.d. *Transportstyrelsen: Vägrafik/Buss- och Godstrafik/Mått och vikt/Grundregler.* [Online] Available at: https://www.transportstyrelsen.se/sv/vagtrafik/Yrkestrafik/Gods-och-buss/Matt-och-vikt/Grundregler/
[Accessed 29 12 2015].

Zhou, J. & Tsai, H.-L., 2012. Hybrid Laser-Arc Welding. In: D. R. Kovacevic, ed. *Welding Processes.* s.l.:InTech.