Analysis and Design of an Overhead Self-launching Movable Scaffolding System for Arsta Railway Bridge, Sweden

Watanapong Hiranmarn[1], Chuan Chuntavan[2], Nuthaporn Nuttayasakul[3] Martin P. Bae[4] and Huang Aiwu[5]

[1]Department of Civil Engineering, Mahanakorn University of Technology, Bangkok, Thailand, 10530

[2,3] Department of Civil Engineering, Academic Division, Chulachomklao Royal Military Academy, Nakorn Nayok, Thailand, 26001

[4,5] NRS Consulting Co.,Ltd., 121/90 RS Tower, 32nd Floor, Ratchadaphisek Road, Din Daeng, Bangkok, Thailand, 10400

E-mail: [1]watanapong@gmail.com [2]cchuntavan@gmail.com, [3]nuthaporn.crma@gmail.com, [4]martin@nrsconsult.com, [5]huang@nrsconsult.com

Abstract

Norwegian specialist, NRS AS, has been appointed by the contractor of Swedish Traffic Authority, Pihl, to undertake the design and supply of a Self-launching Movable Scaffolding System (MSS) for the construction of the Arsta railway bridge in Sweden. The bridge will begin north of Arstaberg station and end just south of Alvsjo goods station. The railway bridge is a single viaduct, pre-stressed solid concrete box-girder bridge. Bridge span length varies from 24.67-34.22m with the average span weight of 20.0 t/m. There are two types of piers, i.e. single and portal, standing up around 10 meters above the ground. The 1.4km long bridge is cast in the MSS – a mold that is moved forward bit by bit until the casting process is completed. The 75m MSS is mounted on the piers that are in the area immediately south of Alvsjo freight rail yard. The scope of the work includes the design, steel fabrication, and supply of ancillary equipment for the MSS. This paper presents several design challenges due to site constraints and the bridge structures itself. These challenges include high impact loads on the MSS due to adverse wind load anticipated while working nearby the moving train, special considerations to ensure efficient installation, bridge concreting and launching of the MSS.

Keywords : Movable scaffolding system, MSS, Pre-stressed concrete bridge, Railway bridge

1. Introduction

Bridge construction especially for a whole span cast in-situ concrete bridge, over deep valleys, water crossings with steep slopes, over highway or railway, or environmentally protected regions can offer many challenges. Conventional Scaffolding or Formwork was formerly built in place and can only be used once. Because of high labor and material cost, the trend today is toward increasing prefabrication, assembly in large units, erection by mechanical means such as "movable forms" and continuing to modify and reuse the forms for other projects. The Movable Scaffolding System (MSS) for bridge construction may offer advantages over conventional method using conventional scaffolding, MSS offers minimal disturbance to surroundings, providing a more concentrated work area for superstructure assembly, and possibly increased worker safety. Movable Scaffolding Systems are conceived to be used in the construction of cast in-situ concrete bridges and they are travelling steel structures supporting the formwork that gives shape to the bridge.

The MSS consists of a support structure spanning between two piers from which formwork is either supported or suspended. The inner formwork (core form) is collapsible and can run on a rail system to allow easy relocation to the next span. The system is designed so that the outer formwork can be opened sufficiently to allow it to pass around the bridge columns during the launching process. After launching, the formwork is closed again and after setting to the correct alignment, placement of reinforcement can start.

The MSS can be divided into two types, namely, (i) underlane (or underslung) and (ii) overlane (or overhead). The underlane type of MSS has two parallel girders which support the formwork. The overlane type of MSS has one or two main girders from which the formwork is suspended. The choice of which type to be used depends on site conditions such as height restrictions, type of bridge deck (e.g. single cell, twin cell, double T) and height of columns.

This development of the Self-launching MSS (SL-MSS) in order to solve the problems related to the difficulties in handling pier support brackets over water as well as on high piers is a world first. This system is able to transfer forward and mount the pier support brackets without any need of an independent crane. The SL-MSS has been successfully used in the construction of several major bridge projects worldwide due to its cost and operational efficiency.

However, the existing problems related to current MSS include requirement of long cycle time, inability to deliver the whole rebar cage simultaneously or all at once, requirement of several block-outs in the superstructure, requirement of hanging bars passing through the superstructure deck to support the formwork, requirement of other equipment necessary for relocation of the supports and, last but not least, the complexity of its operation as well as the labor intensive work.

Moreover, most of the movable scaffolding systems at present have limitations in their operation regarding the high costs of construction manpower and the cost of assembling, dissembling and re-assembling.

This current system provides the new MSS with the self-launching system used for cast-in-situ bridges which can offer many cost-saving advantages to the bridge construction project.

2. Bridge Configuration

This section includes requirements and information provided by the client (the contractor of Swedish Traffic Authority, Pihl) regarding the configuration of the bridge. The railway bridge is a single viaduct, pre-stressed solid concrete box-girder bridge with various span lengths range from 24.67m to 34.22m as shown in Figure 1.

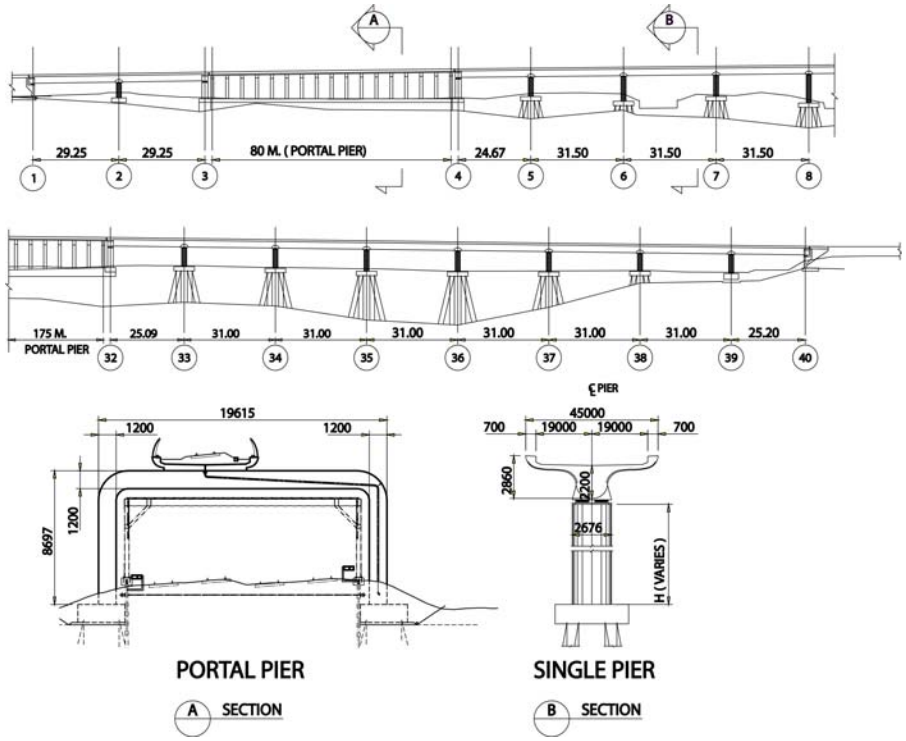


Fig. 1 Bridge structural layout and superstructure

The bridge is constructed as a series of continuous spans with the expansion joints at abutments. It has a minimum horizontal radius of 800m and a maximum longitudinal slope of 1.25%. The bridge superstructure is 9.0m wide and. 2.20m in depth with the span weight of 20.0 t/m. The bridge substructure has pier widths of 2.70m and pier lengths of 1.70m. There are two types of piers, i.e. single and portal. In general, the single piers are for installing the rail system and portal pier areas (175m and 80m) are for the station areas.

3. Design Criteria

3.1 Design Code

The structural calculation of the MSS was performed according to the following design rules and specifications:

3.1.1 Steel structure: Eurocode 3 [1], AISC [2], NS 3472E [3], AASHTO [4], and BS 5950 [5].

3.1.2 Wooden formwork: NS 3470 [6]

3.1.3 Lifting equipment: F.E.M. 1.001 [7] and DnV rules [8]

3.2 Load

The assumed loads and density are as following:

3.2.1 Density of: concrete 2,650 kg/m3, steel 7,850 kg/m3, wood 815 kg/m3.

3.2.2 Working platforms: upper-working platform of top panel formwork are designed for a uniform load of 2.5 kN/m^2

3.2.3 Wind: allowable wind speed for reinforcement and concreting ≤ 22 m/s, for launching ≤ 12 m/s. No operation is allowed (MSS parked) when wind speed is 23-30 m/s. The MSS should be secured in the position when wind speed is 31-68 m/s.

3.3 Deflection

Maximum deflection of formwork during concreting is less than or equal to L/400, when L is span length of formwork.

3.4 Material data

3.4.1 Steel quality: since the MSS will be fabricated in China and shipped to Sweden after complete fabrication, therefore, material properties are based on Chinese standard. Steel grades are Q345 for main member and Q235 for secondary member. Steel strength is depending on the thickness as shown in Table 1 where f_y is the yield strength and f_u is the ultimate strength.

Table 1 Steel properties

Plate thickness, t (mm)	t ≤ 16	16< t≤ 25	25 < t ≤ 36	36 < t ≤ 50	50 < t ≤ 100
Steel Grade	fy / fu, Mpa.	fy / fu, MPa.	fy / fu, MPa.	fy / fu, MPa.	fy / fu, MPa.
Q345 (16Mn) (Profiles/plates)	345/510	325/490	315/470	295/470	275/470
Q235 (Profiles/plates)	235/340	225/340	225/340	215/340	205/340
Young's modulus of elasticity:				210,000 MPa.	
Poisson's ratio:				0.3	
Density:				7,850 kg/m^3	

3.4.2 Fastening elements: the fastening elements are those for connecting each structural member together for example threaded bolts and pin bolts. The strength of these fastening elements depends on size, code, and grade of the elements as shown in Table 2.

3.4.3 Wooden Formwork: design of wooden formwork is based on following:

Plywood: thickness 21 mm, Dokaplex formwork standard.

Wooden material: Norwegian, quality T18 or equivalent NDS.

Formwork ties: ø 15 mm, 900/1100 MPa and ø 20 mm, 900/1100 MPa.

Table 2 Fastening elements properties

Bolt Diameter, t (mm)		0 –16	17-40	41-100	100-160	160 – 250
CODE:	GRADE:	fy / fu, MPa.			f y / fu, MPa.	f y / fu, MPa.
NS-180898-1&2 (Threaded Bolts)	8.8	640 / 800			-	-
NS-180898-1&2 (Threaded Bolts)	10.9	900 / 1000			-	-
EN 10083-1 (Pin Bolts)	34CrNiMo6	980/ 1180	880/ 1080	780/ 980	690/ 880	590/ 780
	40 Cr	785/980				

3.4.4 Material factors (γ_m): Ultimate Limit State (ULS): All parts, $\gamma_m = 1.15$; Service Limit State (SLS): All parts, $\gamma_m = 1.00$

3.5 Design approach

The global anaylsis of the MSS was performed using Eurocode 3 [1]. The analysis of each part in the MSS system was performed using either Eurocode 3 [1] or AISC [2]. For the AISC, the Load and Resistance Factor Design (LRFD) method was used in the design of steel members.

4. Research Methodology and Structural Analysis

4.1 Research Methodology

Research on the design of the MSS was based on more than 30 years experience of our bridge construction equipment. All information from the site supervisors of the bridge construction team were collected, analyzed, scrutinized and finally summarized to build up the best equipment for this bridge in term of performance and efficiency.

The research started from collecting all requirements from the client, studying data from past experience, building up the 3D finite element model, analyzing all load cases acting on the MSS, designing all parts of the MSS based on the worst load case, and finally constructing 3D model for both assembly and operation.

4.2 Structural Analysis

Three dimensional (3D) finite element model of the MSS was constructed based on the nominal geometric and material properties listed in Table 1.

PC-based STAAD-PRO [9] was selected as the software for structural analysis. The analysis was carried out based on the situations that can occur during the MSS operation period which consists of the concreting stage, support relocation stage, launching stage and parking stage. The model composed of Main Girder, Front Nose and Hangers generated by frame member in 3D model. The hanger was analyzed in 2D model separately and the reaction forces from the support of the hanger were used as the input point loads to the 3D structural model of the MSS. Figure 2 shows 3D drawing of the MSS.

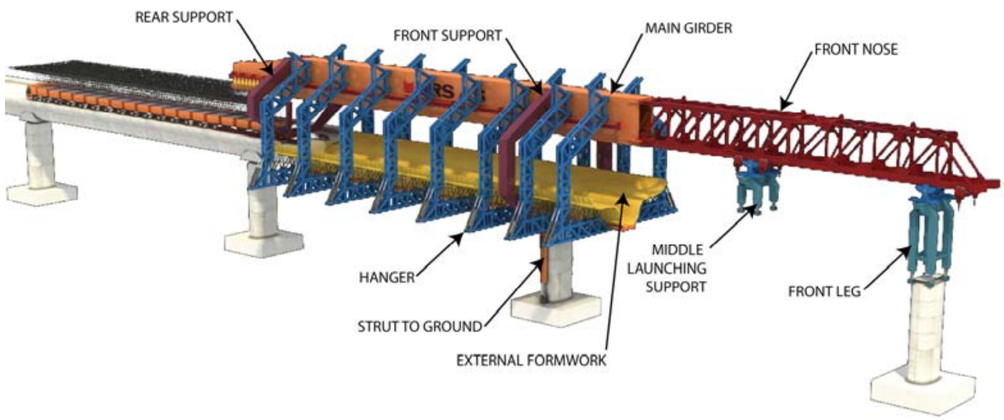


Fig. 2 3D drawing of the MSS

After the 3D analytical model is completed, loads would be applied on the MSS based on the actual weight of concreting bridge span, steel self-weight of MSS, external formworks, and live loads on working platforms. Wind load was also included in the analysis of the MSS for both concreting and launching positions. Figure 3 and 4 show 3D structural model and one example of analysis result when the MSS is subjected to all gravity loads in concreting position.

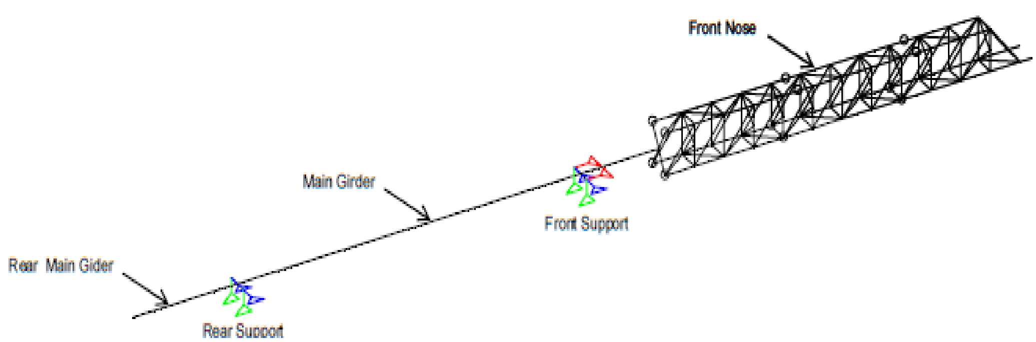


Fig. 3 3D structural model of the MSS

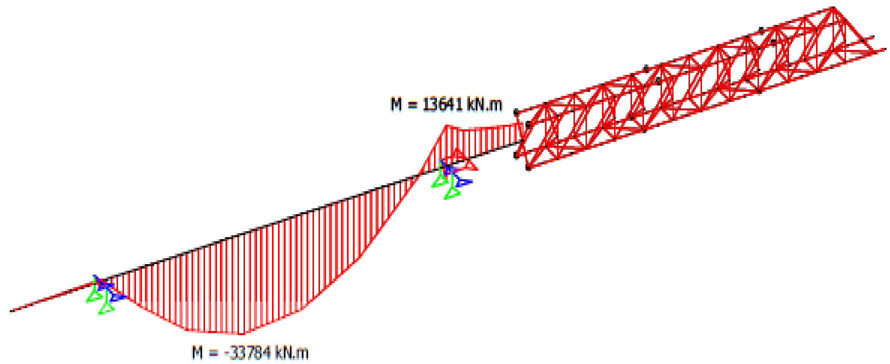


Fig. 4 Resulting moment when the MSS is subjected to all gravity loads

The top parts of the Rear Support and Front Support were designed to pass through web openings of the Main Girder so that the Main Girder can be side shifted along the top part of Rear and Front Support. A huge force transfers from the Main Girder to those supports may affect the shear capacity of the web openings, therefore, careful strengthening around the web openings are necessary. The method proposed by Hagen and Larsen [10] to calculate the shear capacity of steel girders with large web openings, based on the shear buckling capacity, as given by Eurocode 3, was used. The design of shear capacity of girder with opening given by

$$V_{bw,mod,Rd} = \left(1-\frac{D_h}{h}\right)\chi_w c_2 \frac{f_{yw}}{\gamma_{M1}\sqrt{3}} ht \qquad (1)$$

but not larger than

$$V_{bw,modcutoff,Rd} = \alpha_c \left(1-\frac{D_h}{h}\right)\frac{f_{yw}}{\gamma_{M1}\sqrt{3}} ht \qquad (2)$$

D_h is the height of the opening and h and t are the clear web height (depth) between flanges and the web thickness respectively. c_2 is an adjustment factor the secondary effects of the openings. α_c is a cut-off factor and χ_w is the buckling reduction factor for shear as given in EN 1993-1-5 [11].

The moment capacity of girder is given by

$$M_{mod,Rd} = M_{buckl,mod,Rd} = \frac{f_y}{\gamma_{M0}} W_{eff,mod} \qquad (3)$$

$W_{eff,mod}$ is computed by neglecting all parts of the effective web area that fall within the opening. Horizontal reinforcement, if any, is not included

Moreover, for girders with openings the verification of shear and primary moment interaction may be given by

$$\frac{V_{Ed}}{V_{bw,mod,Rd}} \leq 1 \tag{4}$$

$$\frac{M_{Ed}}{M_{el,mod,Rd}} + \left(1 - \frac{M_{f,mod,Rd}}{M_{pl,Rd}}\right)\left(2\frac{V_{Ed}}{V_{bw,mod,Rd}} - 1\right)^2 \leq 1 \qquad \text{for} \qquad \frac{M_{Ed}}{M_{f,mod,Rd}} \geq 1.0 \tag{5}$$

$$\frac{M_{Ed}}{M_{buckl,mod,Rd}} \geq 1.0 \tag{6}$$

V_{Ed} and M_{ed} are the shear force and primary moment, acting at a vertical section through the center of the opening. $M_{pl,Rd}$ is the plastic moment design capacity of the section, considering the effective area of the flanges and the gross area of the web. $M_{el,mod,Rd}$ is the elastic moment design capacity of the girder net section. $M_{buckl,mod,Rd}$ is the moment capacity design of the net section when only the modified effective areas are considered. $M_{f,mod,Rd}$ is the moment capacity design when only the effective flange areas are considered, and the areas required to support the additional flange forces are subtracted.

5. Design of MSS Main Parts

The self-launching movable scaffolding system (SL-MSS) according to this project comprises of:

5.1 Main Girder

Main Girder is the principle bearing component, which transfers the design loads to the supports. Concrete loads are transferred from the formwork into the hanger trusses, which are bolted to the Main Girder. During launching, the Main Girders are supported on the Launching Wagon bogie. During concreting, they are supported by the main jacks, i.e. 2 at the rear support and 2 at the front support. At the front end, there are connections for joining the Nose to the Main Girder. The Main Girder is divided into four sections, length varies from 9.765-11.800m suitable for transportation by container, connected together on site by bolted connections, as shown in Figure 5.

5.2 Rear Nose

Rear Nose which provides a transfer of load to Rear support during casting and launching is equipped with the mono-rail for electrical lifting hoist used for rebar cage loading.

5.3 Hanger Trusses

Hanger Trusses which provides a transfer of load from formwork to main girder during casting. There is the second folding function on the upper part of the hanger trusses which creates the wider opening and the higher position. This will allow the MSS to pass the portal pier area or other obstructions.

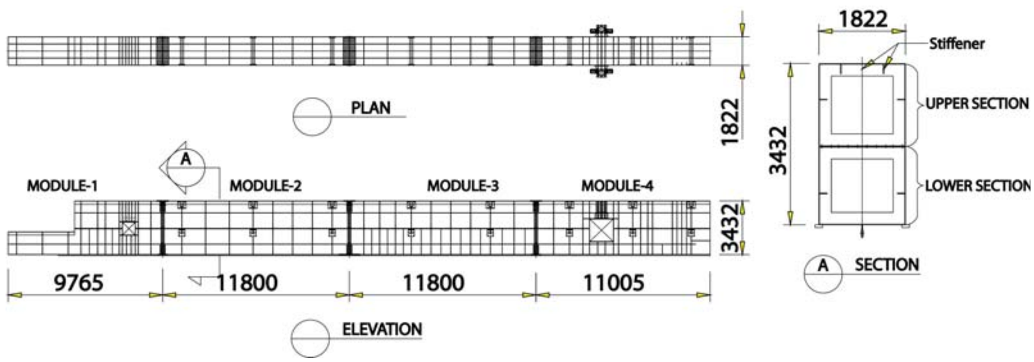


Fig. 5 Main Girder modules and typical cross section

5.4 Rear Support

Rear Support which provides support to the MSS during rebar cage installation, casting, and launching. The rear support can be opened in the center for rebar cage to pass through and unlike the other previous systems that require the additional rear support during casting, the Rear support of this invention is now designed to take the casting load. The foldable legs, parts of the Rear support, are folded up to support directly to the main girder during casting and launching. The rear support main jacks are activated and transfer load to existing bridge. During MSS launching, the rear support main jacks are deactivated and load is transferred through the express rollers to the existing bridge. There are rear support side shifting cylinders equipped at top of the rear support and the main girder. They are used for transverse adjusting of the main girder during launching stage where the main girder must pass through curve spans and for transverse adjustment of the rear support itself before casting. The Rear Support is fixed to the main girder. No other external equipment is required for its relocation.

5.5 Front Support

Front Support which provides support to the MSS during rebar cage installation and casting. The front support is opened at the center for rebar cage to pass through. Once finish placing the rebar cage, tension bars are installed and engaged to the front support to confine the deflection of the front support during the casting stage. Unlike the other previous systems that require the block-outs in bridge structure, there is no part of the front support pass through the bridge structure in this system. Therefore, block-outs are not required. During casting, the front support main jacks are activated and load from the main girder transferred to the front support. The front support legs, which are part of the front support, provide a transfer of load to the column footing. There are front support side shifting cylinders equipped at the top of the front support and the main girder to allow the transverse adjusting of the main girder. The front support is fixed to the main girder. No other external equipment is required for its relocation.

5.6 Front Launching Support

Front Launching Support provides support to the MSS during launching operation. The front launching support is set and secured on the pier top with the launching wagon at the top, which allows the front nose and the main girder to glide or move over to the new set position. The front launching support can be dissembled from pier and suspended to front nose in order to relocate to the next pier.

5.7 Middle Launching Support

Middle Launching Support provides support to the MSS during launching operation. The middle launching support is suspended to the front nose during casting. The middle launching support is moved back and set on already casted concrete and activated to support the MSS during launching.

5.8 Trolley system

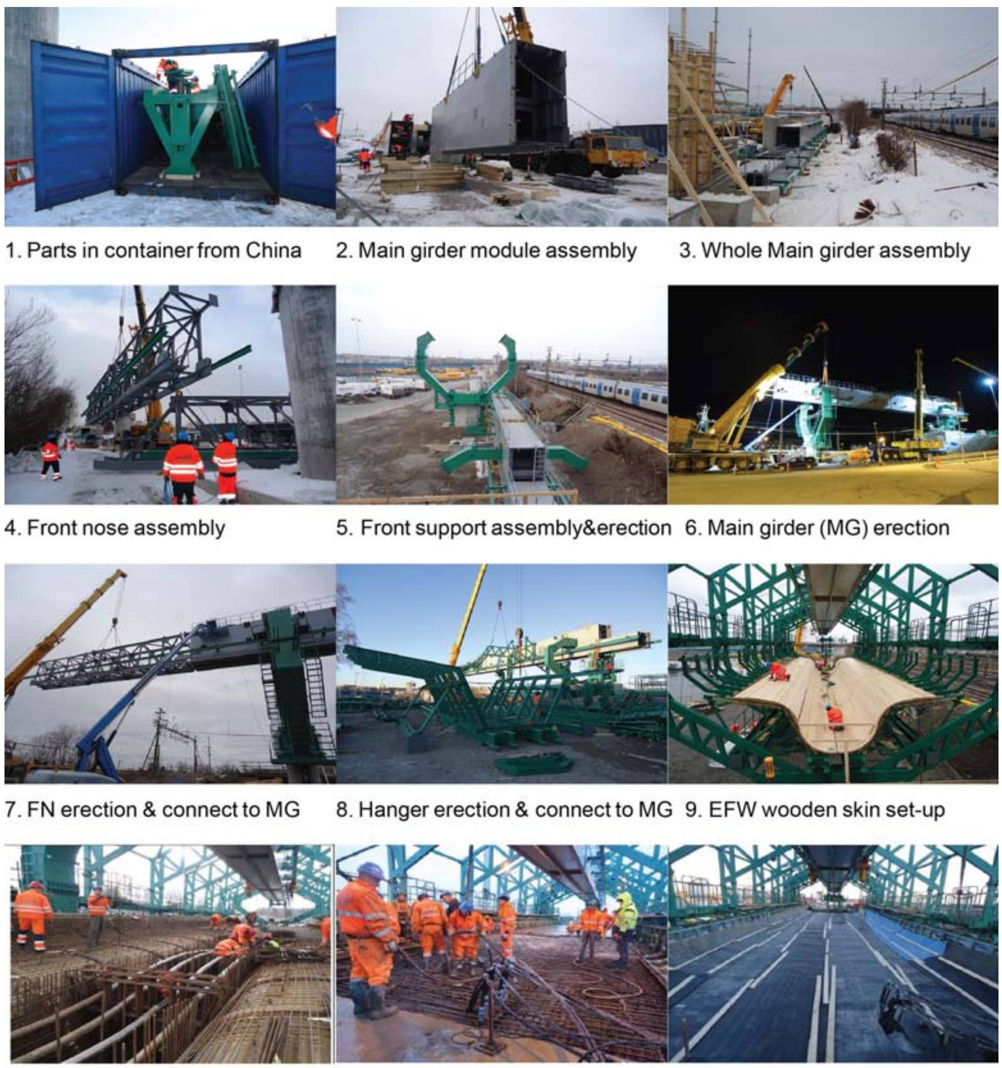
Trolley system provides relocation to the Middle lunching support and the Front launching support and also provides the rebar cage delivery. The trolley system is composed of the mono-rail set along the rear nose, main girder, and front nose and the electrical lifting hoist.

5.9 Formwork

Formwork supported by support frame in this system does not require hanging bars for its hanging. Therefore, there is no obstruction during the rebar cage installation and concreting.

6. Assembling and Erecting Sequence

In order to operate the MSS, the assembling and erecting sequence of the SL-MSS can be described as shown in Figure 6. The MSS is a complex structure which requires a great number of operations to be performed in a safe manner. The safety check lists need to be implemented before starting each operations. Contractor-engineering office shall carefully plan each single operation based on the input given in the operation manual and on the relevant conditions for each single operation. The planning shall be performed in advance to reduce the risk of leaving out important issues. The planning shall include relevant obstructions for each span. Verify that all involved personnel are aware of the operations to be performed and that they are informed about the risks and safety measures involved in the different steps of the operation. Check that the hydraulic system is working properly. All personnel working on the formwork prior to securing with tension bars shall be supplied with a safety harness attached to the Hanger Truss. After bringing in and installing the reinforcement and prestressing steel, now the MSS is ready for casting the first span of the bridge as shown in Figure 7.



1. Parts in container from China 2. Main girder module assembly 3. Whole Main girder assembly
4. Front nose assembly 5. Front support assembly&erection 6. Main girder (MG) erection
7. FN erection & connect to MG 8. Hanger erection & connect to MG 9. EFW wooden skin set-up
10. R/F & Prestressing ducts setup 11. Casting concrete 12. Curing concrete

Fig. 6 Assembling and erecting sequence of the SL-MSS

Fig. 7 Reinforcement and prestressing steels installation

The concreting work is a fast activity, where the workers move continuously along the formwork. The following main safety comments are noted. Workers on the top slab shall be especially careful when vibrating and moving along. The concrete hoses will need to be located within the MSS structure. Attention shall be paid not to damage any of the MSS components.

7. Concreting Sequence and Launching Procedures

7.1 Concreting Sequence

Concreting starts above the front pier of the MSS and continues symmetric both in front and back of the pier, and then working back to the previous span. Based upon past experience, the maximum allowable unbalance during concreting is 100kN (10 tons). This unbalance is defined as the difference of concrete between the right and left sides of the superstructure.

By starting the concrete at the front end of the MSS, the Main Girder will have virtually reached its maximum deflection by the time concreting reaches the previous span. The MSS in concreteing position of the start span is shown in Figure 8.

Fig. 8 The MSS in concreting position for start span during August 2012

7.2 Launching Procedure

The launching condition is the most extensive of all operations. It involves using almost all the facilities of the MSS. The launching method is affected by the obstructions below the formwork, obstructions on the sides of the formwork, already casted concrete sections, radius of spans and span lengths.

During launching, it is essential that all personnel are given specific responsibilities and understand the potential problems that could occur. The main problem when launching through a radius and adjacent to an existing structures will possibly be the launching rail getting jammed in the launching wagon or the hangers clashing with the existing structures or other obstructions.

In addition to the above, it is also necessary to observe any obstructions that may be present beside the bridge as the MSS is launched forward with the hanger trusses together with formwork opened outward.

The launching sequence of the SL-MSS comprises of the concreting and launching stages as the following:

<u>Stage 1</u>

1.1 MSS is set at the concreting position.

1.2 Front support and rear support are activated.

1.3 Middle launching support is suspended to the front nose.

1.4 Front launching support is ready set on top of the next pier.

1.5 Install rebar cage and cast the span.

<u>Stage 2</u>

2.1 Move back and install the middle launching support on the already cast deck.

2.2 Release the main jacks at front support and rear support respectively. Rear support is now on the express rollers.

2.3 MSS is supported by middle launching support and rear support.

2.4 Open the hanger trusses.

2.5 Prepare for launching forward to the next span.

<u>Stage 3</u>

3.1 Launch forward the MSS to the new span until the front support is in same line with the front launching support. During launching, the MSS is supported by front launching support, middle launching support and rear support

3.2 Activate the main jacks at front and rear supports to take load of the MSS. Middle launching support and front launching support are now free.

<u>Stage 4</u>

4.1 Relocate the front launching support to set on the next pier.

4.2 Relocate the middle launching support to suspend to the front nose.

4.3 Close up the hanger trusses. Prepare the MSS for the casting.

4.4 Repeat the stage 1-4 to complete the cycle for the next span.

8. Conclusion

The movable scaffolding system for Arsta Railway Bridge, Sweden, has many advantages over conventional scaffolding because of high efficiency in achieving rapid cycles, lightweight, simple assembly, less manpower, conveniently adaptable to different cross sections (allowing reuse elsewhere). The new invention at Front support eliminate the blockouts and allow faster concrete casting operation. The self launching option allows the contractor to avoid using cranes for pier bracket relocation. Additionally, the prefabricated rebar cage can be lifted and placed by MSS.

9. Acknowledgments

The writers are indebted to all design engineers and draftmans of the NRS Consulting company for their great contributions to this project.

References

[1] Eurocode 3. *Design of steel structures, Part 1-1. General rules and rules for buildings, European Committee for Standardisation (1st Ed.), Comite Europeen de Normalisation (CEN)*, Europäisches Komitee für Normung, Central Secretariat: rue de Stassart 36, B-1050 Brussels, 1993.

[2] AISC. *The American Institute of Steel Construction Inc.*, December 27, 1999. Load and resistance factor design specification for structural steel buildings.

[3] NS 3472E. *Norwegian standard, Steel structures design rules (2nd Ed.)*, published by Norges Standardise-ringsforbund (NSF), Norwegian standards Association, 1984.

[4] AASHTO. *The American Association of State Highway and Transportation Officials, Guide design specification for bridge temporary works*, 1995.

[5] BS 5950. *Part 1, Structural use of steelwork in buildings, Code of practice for design in simple and continuous construction: hot rolled sections*, 1990.

[6] NS 3470, *Norwegian standard, 4th Ed.*, 1989.

[7] F.E.M.1.001: *Rules for design of hoisting appliances (3rd Ed.)*, published by Federation Europeenne De La Manutention, 1987.

[8] DnV Rules: *Rules for planning and execution of Marine operations, Part 2, Chapter 5: Lifting, Det Norske Veritas*, 1996.

[9] STAAD-PRO, *Research Engineers, Inc., US Corporate Headquarters*, 22700 Savi Ranch, Yorba Linda, CA 92687, U.S.A., Tel:(714) 974-2500, Fax: (714) 974-4771, E-Mail:info@reiusa.com, Internet:http://www.reiusa.com

[10] N.C. Hagecenn and P.K. Larsen, *Shear capacity of steel plate girders with large web openings, Part II: Design guidelines*, Journal of Constructional Steel Research, 65(2009), 151-158

[11] EN 1993-1-5 *Eurocode 3-Design of steel structure – Part 1-5: Plated structural elements*, 2006, CEN.