Proposal of Maglev Guideway Girder by Structural Optimization: Civil Works of Center for Urban Maglev Program in Korea

Byeong Moo Jin[1], In Gyu Kim[1], Young Jin Kim[1]
In Ho Yeo[2], Won Seok Chung[2], Jae Suk Moon[3]
[1] Civil Engineering Research Team, Institute of Construction Technology, Daewoo E&C Ltd., Korea
[2] Korea Railroad Research Institute
[3] Korea Rail Network Authority

***Abstract*-An optimized maglev guideway girder system which fulfills the requirements of Center for Urban Maglev Program in Korea is proposed. The design of optimized guideway girder should satisfy the design criteria regarding load conditions (vehicle load and dead load) and deflection conditions due to moving vehicle load. The design criteria have deflection regulation on live load and concrete strength condition on top and bottom ends of the girder. To satisfy these conditions, we define various design variables (DV), state variables (SV) and object function (OBJ) followed by structural optimization process leading to the dimension of the cross section of the guideway girder. General purpose finite element analysis program ANSYS was utilized to perform structural optimization and 3D analysis to check the design criteria. Accordingly proposed maglev guideway girder is compared with the guideway girder systems of the commercial and experimental routes economically and indirectly.**

I. Introduction

A maglev guideway girder is a bridge structure to support the maglev train operation. Unlike ordinary bridge girder, maglev guideway girder essentially has the guideway to guide the maglev train. Maglev train market since the late 1960's in Germany and Japan and the Korean maglev train project since the late 1980's has preferred the following type of girders for straight and curved routes:

- Straight : PSC(Prestressed Concrete) girder
- Curved : Steel box girder

The Center for Urban Maglev Program in Korea will decide the test bed and construct the 1st maglev train lane by 2012. The two main goals of the Center are the improvement of the vehicle performance and the maglev track structure. The maglev track structure has the following goals:

- It should be economical.
- It should be slim in accordance with urban environment.
- It should be light to be constructed more efficiently.

To obtain these improvements for superstructures, authors proposed an optimized cross section of the maglev guideway girder in this paper. Frequently used PSC girder is the most economical girder type in straight route of the road bridge, railroad bridge and the maglev train bridge. The design process follows general procedures of the bridge design, and authors propose the most economical cross section by structural optimization.

II. Basic Concepts of Guideway Girder System

In this study, the basic type for straight route was determined as the superstructure based on PSC girder. The deflections due to live load, i.e., the moving maglev train load are controlled more strictly than those of highway bridges due to general vehicles. The deflection regulations for several maglev systems are as follows.

- KIMM test line, Korea [1] : L/4,000
- Expo Science Park, Korea [2] : L/3,000
- Transrapid [3] : L/4,000
- Kwang-myung AGT, Korea [4] : L/1,000
- Linimo [5] : L/1,5000
- Highway Bridge [6] : L/800
- This study : L/1,500 ~ L/4,000

Also for the construction on urban site, the requirements for superstructure (maglev guideway girder system) are the lightness, the slenderness, and the economic savings. Therefore, we proposed a lightest girder system which is more economic and more slender than any other types of maglev guideway girders. The concept drawing of the proposed PSC U-type girder system is depicted in Fig. 1.

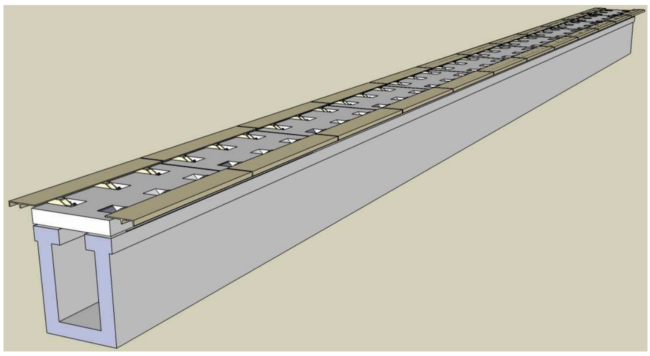


Fig. 1. Concept drawing of PSC U-type girder system with precast deck under development

TABLE I
ALLOWABLE STRESSES OF CONCRETE GIRDER (f_{ck} = 40MPa)

Stage	Description	Values (MPa)
Stage 1: Compressive strength at initial prestressing	$0.8f_{ck}$	32.0
Stage 2: Compressive and tesile strength just after prestressing	$0.55f_{ci}'$	17.6
	$0.75\sqrt{f_{ci}'}$	1.34
Stage 3: Compressive and tesile strength under design load	$0.4f_{ci}'$	16.0
	$1.50\sqrt{f_{ci}'}$	3.0

The design criteria of the maglev train bridge can be summarized as the deflection regulations due to vehicle load in the sense of serviceability and the stresses limits of the girder due to the combination of the dead load and live load. The allowable stresses for concrete compressive strength f_{ck} are described in Table I.

III. STRUCTURAL OPTIMIZATION

The structure is designed according to the design variables (DV), and the state variables and the values of the objective function are determined by the boundary and load conditions. The optimal value (extreme minimum or extreme maximum value) of the objective function is determined by the 1st or 2nd derivative with respect to the design variables. Accordingly the design variable with large influence on the objective function becomes evident during the optimization process, and reasonable design can be established.

The independent variables in an optimization analysis are the design variables. The vector of design variables is indicated by:

$$X = \lfloor X_1 X_2 \cdots X_n \rfloor . \quad (1)$$

Design variables are subject to n constraints with upper and lower limits, that is,

$$\hat{X}_i \leq X \leq \overline{X}_i \qquad (i = 1,\ 2, 3,\ \cdots,n) \quad (2)$$

where : n=number of design variables.

The design variable constraints are often referred to as side constraints and define what is commonly called feasible design space. Now, minimize

$$f = f(X) \quad (3)$$

subject to :

$$g_i(X) \leq \overline{g}_i \qquad (i = 1, 2, 3, \cdots, m_1) \quad (4)$$

$$h_i \leq h_i(X) \qquad (i = 1, 2, 3, \cdots, m_2) \quad (5)$$

$$w_i \leq w_i(X) \leq \overline{w}_i \qquad (i = 1, 2, 3, \cdots, m_3) \quad (6)$$

where f = objective function and g_i, h_i, w_i = state variables containing the design, with lower($\hat{a}$) and upper($\overline{a}$) bounds. The $m_1 + m_2 + m_3$ = number of state variables constraints with various upper and lower limit values.

TABLE II
VARIABLES USED FOR STRUCTURAL OPTIMIZATION

Variables		Decriptions	Lower limit	Upper limit
DV	H	Girder height	1.20	2.50
	B	Girder bottom flange width	0.90	1.75
	B_{top}	Width of upper wing	0.40	0.50
	T_{fb}	Thickness of bottom flange	0.20	0.30
	T_{ft}	Thickness of web	0.20	0.30
	T_w	Thickness of top precast deck	0.20	0.30
	…	Etc.	-	-
SV	f_c	Max. compressive stress Stage 1 Stage 2 Stage 3	-	 $0.8f_{ck}$ $0.55f_{ci}'$ $0.4f_{ci}'$
	f_t	Max. tensile stress Stage 1 Stage 2 Stage 3		 - $0.75\sqrt{f_{ci}'}$ $1.50\sqrt{f_{ci}'}$
	P_t	Prestressing forces		
	…	Etc.		
OBJ	Weight	Weight of girder system		
	H/L	Slenderness of girder system		
	Cost	cost/girder system		

The girder system of maglev train has several design variables, state variables and objective functions as shown in Table II. The objective function can be the weight of the maglev guideway girder, the slenderness in the sense of aesthetics and the total cost including the manufacturing, transferring, construction and management of the girder system. In this study the structural optimization is accomplished to minimize the weight of the girder.

The geometric design variables includes the girder height of the center (H), the width of the bottom flange (B), the thickness of flange and web (T_{fb}, T_{ft}, T_w), the width of the wing part (B_{top}) for the connection between the precast deck and the guide girder. The design variables about material properties are Young's moduli of concrete and steel/tendon, and so on.

In this study, we used general values of material properties and excluded them from the list of design variables. The support parts of the girder, different from the center, should have minimum width of the cross section to apply prestress such that we set the minimum thickness of the concrete wall as 0.4m in the support part.

The stresses and displacements of the finite element model are the state variables. In this study, the maximum compressive or tensile stresses of the top and bottom ends of the concrete girder at each load step, and the maximum deflections under the live load were set to be the state variables.

We utilized general purpose finite element analysis program ANSYS [7] for the structural optimization. 3D solid model of the girder was generated according to the design variables, and linear finite element analysis was performed under the live load.

According to the results of finite element analysis, we decided whether the state variables such as the deflection and stresses are satisfactory or not and minimized the objective function automatically. ANSYS has 7 kinds of optimization algorithm internally and the subprogram approximation method is used among them.

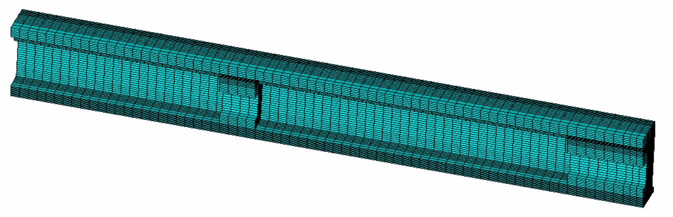


Fig. 2. Finite element model of girder system (1/4 Model, L=25m)

The 3D solid finite element model shown in Fig. 2 is based on the suggest maglev guideway girder in Fig. 1. Considering the symmetry of the geometry and load, 1/4 of the entire girder was modeled.

IV. OPTIMIZATION RESULTS

The optimized shapes of the PSC girder with respect to each span and deflection regulation are described in Table III. Table IV shows the optimized weight of each girder, stresses of the concrete on the top and bottom ends according to the live load and the weight ratio. The appropriate span length to minimize the concrete weight is decided to be 25m (than 30m) for a route with full length of 1km. In the last step, additional analysis was performed for the deflection regulation of L/2,000.

V. STRUCTURAL ANALYSIS OF OPTIMIZED GIRDER

In the previous part, a weight optimized cross section was decided. In this part, we showed the structural analysis results of the cross section for each load case. Five load cases are combinations of the dead load, live load and the prestressing forces of the tendon (Table V). The maximum deflection and stresses of the top and bottom ends of the guideway girder are presented in Table V. Fig. 3~ Fig. 7 show the deformed shapes of the guideway girder and stress distributions of it. Both dead load state (load case 4: DL+PS) and live load state (load case 5 : DL+PS+LL) satisfy the design criteria (Table I) regarding the deflection and stresses.

TABLE III
THE SHAPE OF PSC GIRDER OPTIMIZED BY WEIGHT

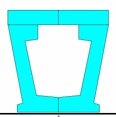
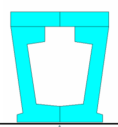
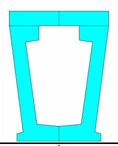
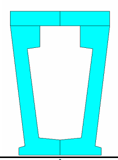
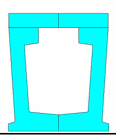
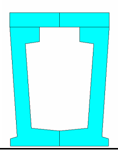
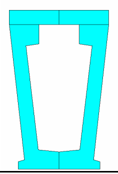
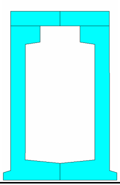
Span Length L (m)	Deflection Regulation			
	L/1,500	L/2,000	L/3,000	L/4,000
25.0				
30.0				

TABLE IV
STRUCTURAL OPTIMIZATION RESULTS OF GUIDEWAY GIRDER SYSTEMS

Items	Deflection Regulation							
	L/1,500		L/2,000		L/3,000		L/4,000	
L (m)	25.0	30.0	25.0	30.0	25.0	30.0	25.0	30.0
H (m)	1.402	1.625	1.515	1.837	1.794	2.183	1.991	2.320
B (m)	0.902	1.165	0.978	1.133	0.841	0.909	0.922	1.357
B_{top} (m)	0.400	0.400	0.469	0.400	0.400	0.401	0.403	0.400
T_{fb} (mm)	200	223	214	206	201	234	208	229
T_{ft} (mm)	200	211	208	200	202	265	293	223
T_w (mm)	200	200	200	200	200	202	200	200
A[1]	-4.76 5.72	-4.99 5.33	-3.98 4.72	-4.16 4.56	-3.17 3.72	-3.19 3.73	-2.62 3.14	-2.74 2.74
B[2]	16.25	20.00	12.50	15.00	8.33	10.00	6.25	7.50
C[3]	67.07	92.90	73.75	98.40	79.06	109.0	86.50	121.5
D[4]	2.68	3.10	2.95	3.28	3.16	3.63	3.46	4.05
E[5]	91.0	126.0	100.0	133.4	107.2	147.8	117.3	164.1
F[6]	40	33	40	33	40	33	40	33
G[7]	2,682	3,066	2,950	3,248	3,162	3,597	3,460	4,010
H[8]	91.0	103.9	100.0*	110.1	107.2	121.9	117.3	135.9

[1] A: Max, Stress at top and bottom of the girder (MPa),
[2] B: Max. Deflection (mm), [3] C: Weight (ton),
[4] D: Weight per unit length (ton/m), [5] E: Weight ratio (%),
[7] F: No. of girders in 1km, [8] G: Total weight of girders in 1km (ton),
[9] H: Weight ratio in 1km (%)
* Weight ratios are normalized by the values of L/2,000 case.

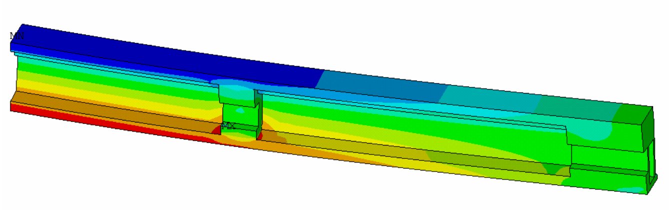


Fig. 3. Deformation and stress distribution (DL: Dead Load)

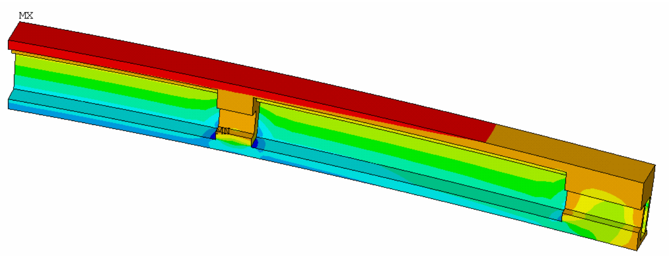


Fig. 4. Deformation and stress distribution (PS: Prestressing)

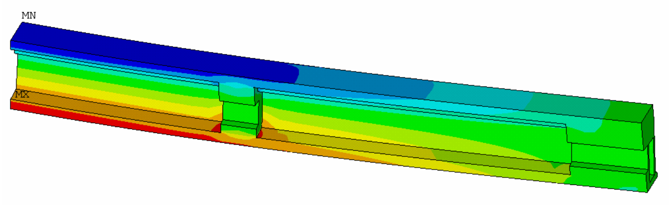


Fig. 5. Deformation and stress distribution (LL: Live Load)

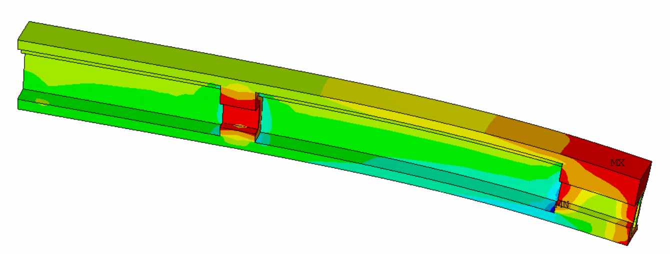


Fig. 6. Deformation and stress distribution (DL+PS)

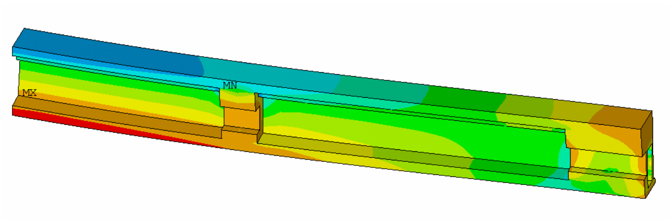


Fig. 7. Deformation and stress distribution (DL+PS+LL)

TABLE V
FINITE ELEMENT ALYSIS RESULTS FOR FIVE LOAD CASES

Load Cases	Deflections at Center (mm)	Stresses at Girder Bottom (MPa)	Stressse at Girder Top (MPa)
(1) Dead Load (DL)	-0.0154	5.79	-4.85
(2) Prestressing (PS)	0.0168	-8.34	2.26
(3) Live Load (LL)	-0.0125	4.73	-4.07
(4) DL + PS	0.0017	-2.77	-2.55
(5) DL + PS + LL	-0.0105	1.97	-6.57

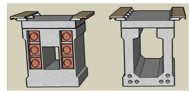
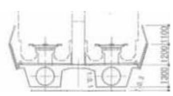
VI. COMPARISONS OF GUIDEWAY GIRDER SYSTEMS

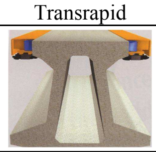
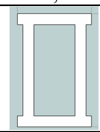
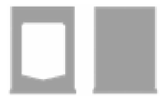
Authors performed indirect comparison of economical efficiency between the maglev guideway girder with optimized cross section proposed in this study and those of other commercial or test route (Table VI). The proposed girder system has lower girder height than other girders such that it fits more in the urban area aesthetically in the case of L/2,000 or L/4,000 deflection regulations. Again due to light weight of the proposed girder system, it is economical and easy to construct.

VII. CONCLUSIONS

In this study, an optimized cross section of the superstructure for the maglev train bridge was proposed through the structural optimization. The proposed section is expected to be more than 50% lighter and more than 25% slenderer than the current commercialized Linimo and Transrapid girder. Besides, compared with previous research results(KIMM test line, Expo Science Park line) and AGT standard cross section, it seems to be a strongly comparative maglev guideway girder system.

TABLE VI
COMPARISONS OF GUIDEWAY GIRDER SYSTEMS

Shape / Items	Proposed girder		Linimo	AGT, Korea
				
L (m)	25.0	25.0	30.0	30.0
H (m)	1.51	1.99	2.5	1.92
H/*L*	0.0604	0.0796	0.0833	0.0640
A[1]	2.3t/m	2.3t/m	1.78 t/m	53 ton
B[2]	L/2,000	L/4,000	L/1,500	L/1,000
C[3]	12.5	12.5	20.0	9.94
D[4]	73.7	86.5	232.0 (1/2 section)	165.93 (1/2 section)
E[5]	2.948	3.460	7.733	5.531
F[6]	100.0*	117.4	262.3	187.6

Shape / Items	Transrapid	KIMM, Korea	Expo Park, Korea
			
L (m)	25.0	25.0	25.0
H (m)	2.20	2.06	1.90
H/*L*	0.0880	0.0824	0.0760
A[1]	2.4 t/m	1.86 t/m	2.5 t/m
B[2]	L/4,000	L/4,000	L/3,000
C[3]	6.25	6.25	6.98
D[4]	143.3	88.6	106.4
E[5]	5.732	3.544	4.256
F[6]	194.4	120.2	144.4

[1] A: Live Load, [2] B: Deflection regulation, [3] C: Deflection (mm),
[4] D: Weight of girder (ton), [5] E: Weight per unit length (ton/m), [6] F: Ratio (%)
* Weight ratios are normalized by the values of proposed girder with L/2,000.

ACKNOWLEDGMENT

This study is done by the support of Center for Urban Maglev Program, and authors are appreciating to the program.

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