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Behavior analysis of aerial tunnel maintenance truss platform with high tensile steel UL-700

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Abstract. The goal of this study is to investigate structural analysis and behaviors of an innovative aerial work platform truss frame whose ductility is improved by using high strength-steel UL-700. The present space truss frame can move or stop through tunnels for maintenance constructions by automatic facilities and workmanship within standardized limited building lines of tunnel. Most of all, this method overcomes problematic, which is to block cars during construction periods, seriously, of typical methods like as using truck and scaffolds for tunnel maintenance. According to evaluated appropriate design results of space truss frames of numerical examples by using a commercial MIDAS GEN program, it is verified that design parameters such as layered size, cross-sectional size, and steel material of the present space truss frame are determined to depend on characteristics such as lanes or shape of road tunnels.

Keywords: road tunnel; maintenance; aerial work platform; blocking transportations; MIDAS GEN; UL-700

1. Introduction

Infrastructure is a wide-ranging term that describes the framework and structural characteristics of a location or activity. Generally infrastructure refers to such tangible and physical facilities as buildings, equipment, roads, tunnels, bridges, harbors, rail networks, airports, gas and electrical power plants.

For increasing industrial development, infrastructures have to be equipped and reinforced essentially to country. Reducing constructional period and saving cost of them are the primary concern of civil and architectural engineers by which mega structures are both built and repaired or controlled (Elena 2007). Limited budget such as resource or money leads to change to the point in which engineers or designers should make an effective use of them instead of buildings them. An increasing significance is now placed on maintenance of infrastructures since their “effective use” is seriously called for.

Road tunnel dealt with in this study is reportedly extended to 2,008 km altogether in republic of Korea under the number of 1,382 (Lee *et al*. 2012) as shown in Fig. 1. As can be seen in Fig. 1, rational and specific ways (Asakura and Kojima 2003) for maintenance of existing tunnels are more urgent than building new tunnels to save constructional costs based on limited budget.

In general, in order to prevent structural disaster (Jiang and Wang 2012) such as collapses, tunnel maintenance works (John 2006, Lee 1998, World Road Association 2010) are classified with inspection, investigation, measure, reinforcement, and cleaning, which diversely occur over

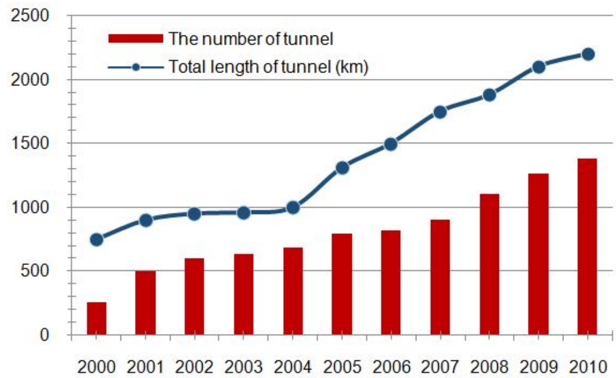

Fig. 1 The total length and number of road tunnel in Korea

two times pro tunnel (Norwegian Public Roads Administration 2004) for life cycle control. It is similar to temporary or scaffolding works of main structures.

By using classical equipment and methods (Terato *et al*. 2008), problematic of typical maintenance works (Sato i. 1996) of tunnel are described in Fig. 3 and Table 1, including examples of tunnel temporary works for maintenance in Fig. 2. As can be seen, it has a severe problematic to carries out maintenance construction of tunnels with totally or partly blocking vehicles and transportations in tunnels. In especial, traffic jam may occur in rush hour owing to this classical construction method.

In order to resolve this problem to maintenance constructions of tunnel, a specific space truss frame apparatus (Lee *et al*. 2015, Lee *et al*. 2016) only moving inside of a so-called limited building line (KBC 2009, IBC 2009) is presented in this study.

This study is divided into 5 sections. Following section 1 to describe scope, objective, and organization in this

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Fig. 2 Examples of tunnel temporary works

(a) TC lift (b) Oil jack lift (c) Scaffolding frame moving

Fig. 3 Typical equipment of temporary works

Table 1 Equipment of temporary works and their problems for tunnel maintenance

Equipment for temporary works	Temporary works for maintenance and control		Problematic of typical methods for maintenance and control	
	Technical basement for works	Location for installation	Aspect to ordering organization (Government, office and etc.) / Builder (Construction company)	Aspect to tunnel users
TC lift for movement	Automatic lift type	On the load or rail into tunnels	- depending on site environment such as tunnel scale, and equipment which tunnel consists of - Overload of workmanship due to uncertainty such as installation and movement of equipment - Insufficiency of standards of tunnel false works - Increasing construction period - Increasing of construction cost - Restriction of day or night time for temporary works	- Inconvenience of pass of tunnel due to block of loads - Disturbance of goods traffic
Oil jack lift	Automatic oil jack type	On the load or rail into tunnels		
Scaffolding frame	Assembling type among scaffolds	On the load or rail into tunnels		

study, Section 2 presents problematic of classical method to carry out tunnel maintenance works. In Section 3, an innovative space truss frame apparatus are described as alternative to overcome the problem. Numerical examples to verify structural behaviors of the space truss frame apparatus are studied in Section 4, and the conclusions are presented in Section 5.

2. Problematic of classical tunnel maintenance works

As shown in Fig. 2, Fig. 3, and Table 1, It is a dilemma to accomplish both preventing the problematic, i.e., block of moving vehicles, and proceeding favorably typical maintenance construction in tunnels. This situation is a so-called physical contradiction (Cui *et al*. 2011, Lee and Shin 2014) which has the format given element of the system should have characteristic “A - blocking vehicles in tunnels” in order to realize required function - proceeding maintenance construction - to solve problem and this element should have characteristic “non-A” in order to satisfy existing limitations and requirements.

The existing methodology results in blocking road lanes in tunnel originally to take working areas for maintenance constructions. Therefore, it can be found that the problem, i.e., achievement both the construction of maintenance and the movement of vehicles, cannot be solved by using classical equipment and methods shown in Fig. 3.

As shown in Fig. 4, especially, maintenance works of tunnels cannot be carried out in rush hour which traffic jam may often occur. Traffic jam could be getting worse owing to blocking lanes of road tunnels, when maintenance constructions execute in tunnel in rush hour. This means limitation of construction time.

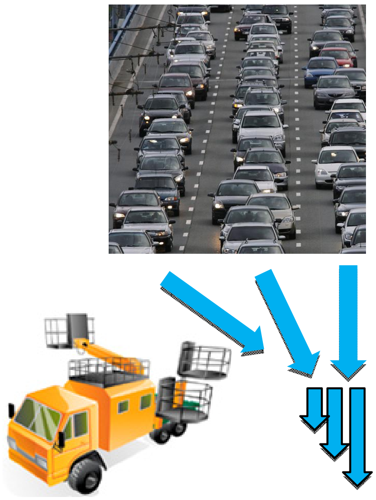


Fig. 4 Traffic jam problem in city due to maintenance constructions of tunnels

Fig. 5 Examples of tunnel equipment for supporting unfinished tunnels

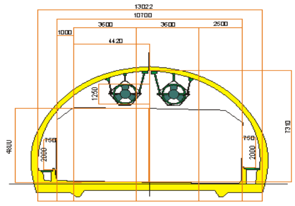
3. New apparatus for tunnel maintenance works

By utilizing tunnel spaces outside of a so-called limited building line, an innovative space truss frame structure is devised in this study, and it can move or stop through tunnels by using automatic facilities and workmanship inside of standardized limited building lines of tunnel. Most of all, this method overcomes the problematic, which is to block vehicles during construction periods, i.e., typical methods using trucks and scaffolds for tunnel maintenance.

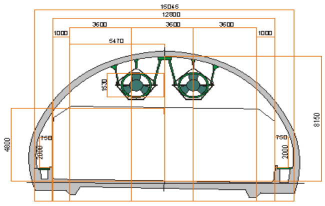
Fig. 5 shows site examples of tunnel equipment for supporting unfinished tunnels. The equipment supporting tunnels is contacted at surface of tunnel and there is a passage. Maintenance such as inspection and repair of tunnels are also directly related to surface of tunnels. It differs with examples of Fig. 5 with respect to objective of construction, but may take hints to make a new idea or an innovative apparatus for tunnel maintenance constructions from them.

Fig. 6 describes useful spaces outside of limited building lines of height and width depending on sizes of road tunnels. Since spaces on the inside of limited building lines are a main passage of vehicles by law, nobody invade the space for maintenance works of tunnels (World Road Association 2010).

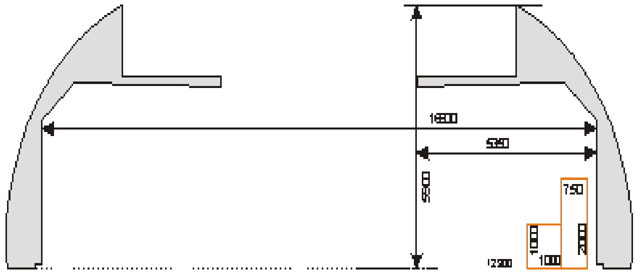
As can be seen, height of useful spaces is all the same to 2, 3, and 4 lane tunnels. Width of useful spaces of 2, 3, and 4 lane tunnels is, respectively, 10.7 m, 12.8 m, and 16.8 m. The developed useful space can be an appropriate site in which maintenance works of tunnels carry out.



(a) Two lane road tunnel



(b) Three lane road tunnel



(c) Four lane road tunnel

Fig. 6 Useful spaces fixed on the outside of limited building lines of height and width depending on sizes of road tunnels

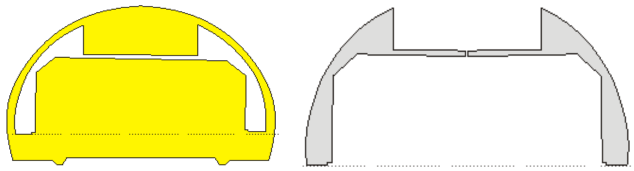


Fig. 7 Useful spaces for maintenance works of tunnels

According to Fig. 6, it can be found that useful spaces to make maintenance works of tunnels are a white or gray domain as shown in Fig. 7. Therefore it is a significant interest what is installed in the useful spaces to carry out effective maintenance works of tunnels.

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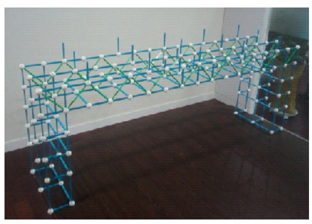
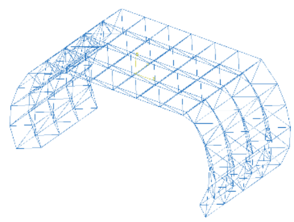


(a) Space truss frame of box shape



(b) Space truss frame of curved shape

Fig. 8 Space truss frame of box and curved shapes

Table 2 Basic modules of temporary space truss systems

Classification	2 Layers	3 Layers	4 Layers
Upper span of temporary system (m)	9.76 × 3 (2 Lanes)	9.76 × 4.5 (2 Lanes)	9.76 × 6 (2 Lanes)
	12.20 × 3 (3 Lanes)	12.20 × 4.5 (3 Lanes)	12.20 × 6 (3 Lanes)
	14.64 × 3 (4 Lanes)	14.64 × 4.5 (4 Lanes)	14.64 × 6 (4 Lanes)

Table 3 Size of temporary space truss systems

Classification	*B*		*H*	
	Total width	Max. width	Total height	Max. height
2 Lanes	12.3 m	10.7 m	5.4 m	4.8 m
3 Lanes	14.4 m	12.8 m	5.4 m	4.8 m
4 Lanes	18.2 m	16.6 m	5.4 m	4.8 m

make maintenance works of tunnels are a white or gray domain as shown in Fig. 7. Therefore it is a significant interest what is installed in the useful spaces to carry out effective maintenance works of tunnels.

Fig. 8 shows the innovative apparatus of space truss frames which can be inserted and then acted in the useful spaces. Owing to curved corner of tunnels, Fig. 8(b) is recommended to move through tunnels. Fig. 8(a) occurs interference owing to sharp corner.

Table 4 Strength of materials

Item		Description
Steel pipe	STK500	· F_y = 325 MPa (Whole member of framework)
	UL-700	· F_y = 590 MPa (Whole member of framework)

Table 5 Analysis program

Item	Description	Remarks
MIDAS GEN	· To examine safety with 3D analysis · Static analysis with wind load and dynamic analysis with seismic load	Ver.7.95

4. Analytical test of space truss frame apparatus

4.1 Setting design conditions

Basic modules of an evaluated temporary space truss system with 4 layers sketched in Fig. 8(b) is described in Tables 2 and 3, and they depend on the upper span and layers of the temporary system. Boxed shape truss is typical type and is not conformed to the given tunnel's maintenance due to corner interference. Therefore curved shape truss is considered for numerical tests in this study.

Size of temporary space truss systems is shown in Table 3. Here Max. Width and Max. Height are decided by limited building lines. Maximum estimated height of the upper base plate in consideration of the intervention of the tunnel ventilation system is assumed to be Max. 0.6 m.

Strength of materials of truss typed temporary structures shown in Table 4 is normal steel STK500 and high strength steel Ultra-Light 700 (UL-700) (Lee and Shin 2015a, b, Kim 2010) of steel pipes.
Analysis program is MIDAS GEN Ver.7.95 (MIDAS 2012) as shown in Table 5. Applied references are shown in Table 6 to carry out structural analysis.

In this study, fixed and live loads are applied in Table 7 in KBC (2009) and IBC (2009). The design rationales of the wind and seismic loads were calculated conservatively. Wind loads are also given to temporary space truss systems

Table 6 Applied references

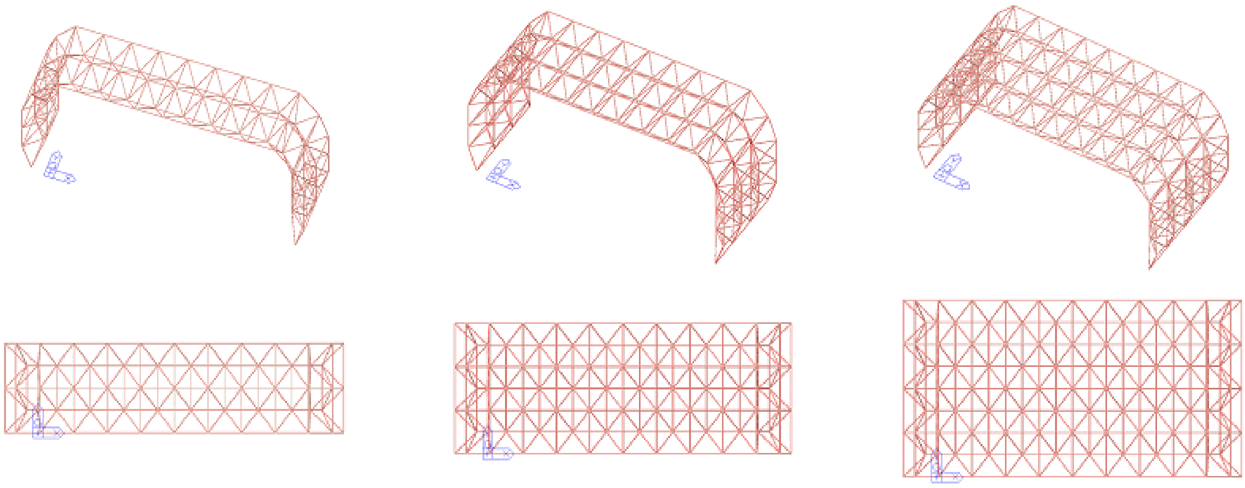
Classification	Description	Drafted in	Remarks
Structural design	· "Regulation for Structural Standard of Building" in Enforcement Decree of the Building Act · Code for Structural Design of Building (KBC 2009)"	2009	Ministry of Land, Transport and Maritime Affairs, Architectural Institute of Korea
Steel structure	· Code for Steel Structure Design · Limited State Design Code of Steel Structures and Commentary	2009	
Seismic·wind-resistant design	· "Regulation for Structural Standard of Building" in Enforcement Decree of the Building Act · Code for Structural Design of Building (KBC 2009)"	2009	

Table 7 Fixed and live loads

Classification	Design load
Fixed load	· To calculate the load in consideration of the self-weight load of the framework and finishing material · Base Plate of Temporary Construction Material: 30 mm (THK)×20 kN/m^3 (Unit Load) = 0.6 kN/m^2 (Unfactored Load)
Live load (kN/m2)	· To calculate the load conservatively in consideration of the catwalk load of the general space frame · 1~ 1.5 kN/m^2 (Unfactored Load)
Wind load	· V_0 = 30 m/sec, Wind Exposure = D, Significance Factor (I_w) = 0.9 (Significance 3)
Seismic load	· Regional Factor (A) = 0.22, Site Classification (S_d), Significance Factor (IE) = 1.0 (Class II), Response Modification Factor (R) = 3.0

Table 8 Wind loads

Classification	Basic design wind speed (V_0)	Wind exposure	Significance factor (I_w)	Topographic factor (K_{zt})	Gust effect factor (G_f)
Factor	30m/sec	Class D	0.9	1.0	X:1.8, Y:1.8



(a) 2 layers (b) 3 layers (c) 4 layers

Fig. 9 Analysis modeling

as shown in Table 8 in KBC2009 and IBC. Allowed horizontal displacement is assumed to be a value of height divided by 500. Seismic load is not considered in this study.

4.2 Analysis method

This temporary system (space frame) aims to design the framework member system based on the elastic analysis. The analysis is conducted through the comparison of a different number of lanes in the temporary system and the comparative review of the external diameters and thicknesses of frames and the different number of layers in the system.

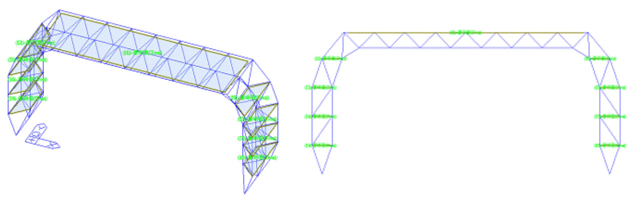
4.2.1 Modeling data

This temporary system is the space frame in a tunnel, modeled in the truss type where a pin moves in an end part. With a width of 10.7~16.6 m (depending on lanes) and a height of 4.8 m, the system is designed within the limited building line in consideration of the interference of finishing and equipment.

4.2.2 Loading range

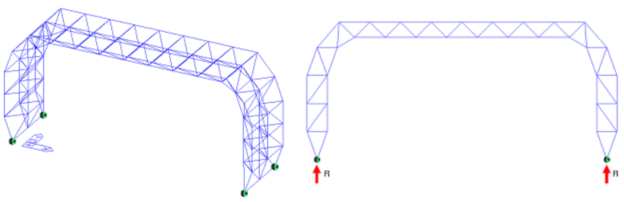
As shown in Fig. 10, the floor load is placed vertically at each member of the framework, reflecting the upwind and downwind conditions on the upper base plate (refer to the load case).

Considering the wind path in the tunnel, WX can be ignored in calculating the wind load, but the external wind



(a) Iso view (b) Front view

Fig. 10 Loading conditions



(a) Iso view (b) Front view

Fig. 11 Location of reaction points

Table 9 Comparison between STK500 and UL-700

Classification	STK500	UL-700
Size of member	Φ48.6×2.3	Φ48.6×1.8
Yield strength (MPa)	325	595
Unit weight (kg/m)	2.63	2.08
Quantity (kg/Frame)	299	237

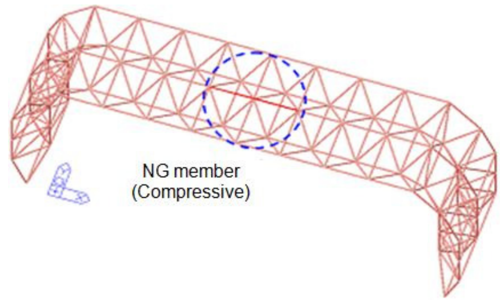
pressure at a right angle to the base plate shall be considered.

Fig. 11 shows the reaction points. In consideration of the movement of temporary construction materials in the tunnel, the materials are moved with rollers in the Y-dir and each support point has 4 (2×2) reaction points.

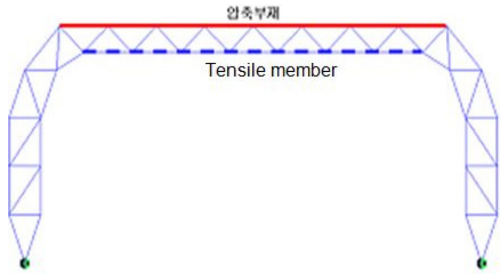
4.3 Analysis results

The following results are from analysis of the framework members. Table 9 compares the two steel grades: UL-700 and STK500, which were compared based on a model with a width of 10.7 m and a height of 4.8 m. The results are basic information for size optimization (Ahrari and Atai 2013, Degertekin and Hayalioglu 2013) of aerial work platform truss structures under the conditions of fixed shapes as shown in Fig. 9.

Analysis results of truss typed temporary structures with 2 lanes and 2 layers are shown in Fig. 12 and Table 10.



(a) STK500 Model NG Member (2 Lanes)



(b) Tensile, Compressive Member (2 Lanes)

Fig. 12 NG members

Table 10 Comparison between STK500 and UL-700

Classification	STK500	UL-700
Judgment	NG for upper member of temporary construction materials	OK
Number of NG members	2 Members	-
Critical load case	1.2D + 1.6L (sLCB2)	1.2D + 1.6L (sLCB2)
Axial force	-40.537 kN (Compression)	-40.129 kN (Compression)
Ratio	1.042 > 1.0	0.905 < 1.0

Table 11 Performance comparisons of STK500

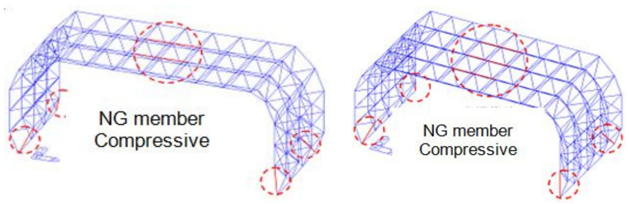
Classification		Φ30.0	Φ40.0	Φ48.6	Φ50.0	Φ60.0
Judgment	18T	NG (Ratio = 102.97)	NG (Ratio = 3.215)	NG (Ratio = 1.365)	NG (Ratio = 1.262)	OK (Ratio = 0.835)
	23T	NG (Ratio = 83.610)	NG (Ratio = 2.012)	NG (Ratio = 1.042)	OK (Ratio = 0.971)	OK (Ratio = 0.658)
	28T	NG (Ratio = 71.274)	NG (Ratio = 1.536)	OK (Ratio = 0.854)	OK (Ratio = 0.799)	OK (Ratio = 0.548)
	33T	NG (Ratio = 62.779)	NG (Ratio = 1.272)	OK (Ratio = 0.731)	OK (Ratio = 0.685)	OK (Ratio = 0.473)

Table 12 Performance comparisons of UL-700

Classification		Φ30.0	Φ40.0	Φ48.6	Φ50.0	Φ60.0
Judgment	18T	NG (Ratio = 57.757)	NG (Ratio = 2.093)	NG (Ratio = 0.905)	NG (Ratio = 0.834)	OK (Ratio = 0.535)
	23T	NG (Ratio = 46.914)	NG (Ratio = 1.385)	NG (Ratio = 0.690)	OK (Ratio = 0.638)	OK (Ratio = 0.417)
	28T	NG (Ratio = 40.009)	NG (Ratio = 1.091)	OK (Ratio = 0.517)	OK (Ratio = 0.529)	OK (Ratio = 0.345)
	33T	NG (Ratio = 35.254)	NG (Ratio = 0.922)	OK (Ratio = 0.493)	OK (Ratio = 0.457)	OK (Ratio = 0.299)

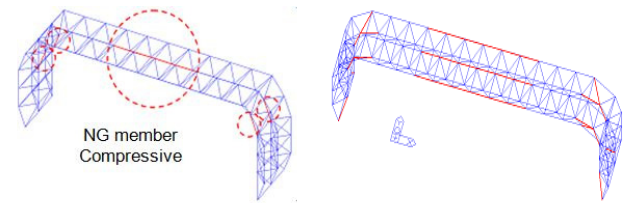
Table 13 Performance comparisons of a different number of layers (Φ48.6×1.8, UL-700)

Classification	2 Layers	3 Layers	4 Layers
Judgment	OK	NG	NG
Number of NG members	-	8 Members	10 Members
Critical load case	1.2D + 1.6L (sLCB2)	1.2D + 1.6L (sLCB2)	1.2D + 1.6L (sLCB2)
Axial force	-40.129 kN (Compression)	-59.623 kN (Compression)	-79.51 kN (Compression)
Ratio	0.905 < 1.0	1.112 > 1.0	5.147 > 1.0



(a) 3 Layers (b) 4 Layers

Fig. 13 NG members by layers (Φ48.6×1.8, UL-700)



(a) 3 Layers (b) 4 Layers

Fig. 14 NG members by Lane Width (Φ48.6×1.8, UL-700)

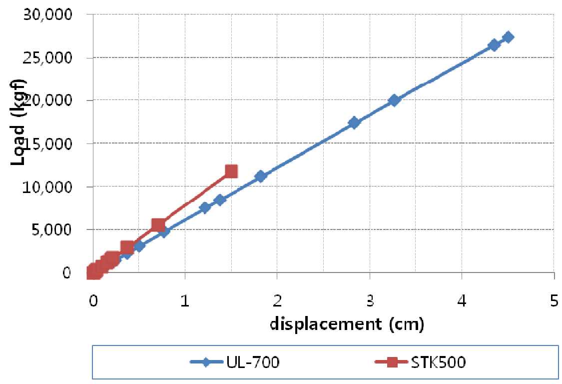


Fig. 15 Comparisons between STK500 and UL-700

As shown in Table 10, the 2 compressive members in the upper part of the temporary construction materials are judged as NG in Φ48.6×2.3 (STK500), which shows that generally a loading condition with a 1.2D + 1.6L (factored load) (KBC 2009, IBC 2009), is the critical load.

On the contrary, although UL-700 is only 0.5 mm thick, it has much higher yield strength than STK 500, making it suitable for the member design of the 2-lane system.

Tables 11 and 12 present performance comparisons of different external diameter and thickness of truss members by using STK500 and UL-700, respectively. The analysis modeling used the 2-lane-based width and the ratio of thickness to diameter was added in each case. Table 11 and 12 compare and analyze the 1.8~3.3 mm-thick steel pipes with diameters ranging from 30.0 mm to 60.0 mm. As can be seen, analysis results indicate that the 48.6 mm-diameter STK-500 should have a thickness exceeding 2.8 mm and the 48.6 mm-diameter UL-700 should have a thickness between 1.8~2.3 mm. Table 13 shows performance comparisons of a different number of layers by using UL-700.

As can be seen, the results of a bearing capacity comparison of a different number of layers indicate the member's yield strength was exceeded in all the critical load cases (1.2D+1.6L) as the number of layers increases. These results show that a compressive fracture happened as the stress was concentrated at a reaction point on the load-supporting members of both sides. In addition, compared with the 3-layer or the 4-layer systems, the 2-layer system is more effective in terms of load de-concentration and the inevitable increase in layers requires the proper selection of steel type and quantity of increase.

Fig. 14 and Table 14 show the comparison of different lane widths on bearing performance. Two, three, and four lanes were modeled and their widths were 10.7 m, 12.8 m and 16.6 m, respectively.. As shown in Table 14, all members satisfied the required bearing capacity in the

Table 14 Performance comparisons of a different number of Lanes (Width) (Φ48.6×1.8, UL-700)

Classification	2 Layers	3 Layers	4 Layers
Width	10.7 m	12.8 m	16.6 m
Judgment	OK	NG	NG
Number of NG members	-	8 Members	34 Members
Critical load case	1.2D + 1.6L (sLCB2)	1.2D + 1.6L (sLCB2)	1.2D + 1.6L (sLCB2)
Axial force	-40.129 kN (Compression)	-55.446 kN (Compression)	-92.231 kN (Compression)
Ratio	0.905 < 1.0	1.24 > 1.0	4.294 > 1.0

Table 15 Optimal designs of truss typed temporary structures for 2 lanes

Classification	STK500	UL-700
External diameter	48.6 mm	48.6 mm
Thickness	2.8 mm	1.8 mm
Ratio	0.854 < 1.0	0.905 < 1.0
Judgment	OK	OK

Table 16 Optimal designs of truss typed temporary structures for 3 lanes

Classification	STK500	UL-700
External diameter	48.6 mm	48.6 mm
Thickness	3.3 mm	2.3 mm
Ratio	0.943 < 1.0	0.917 < 1.0
Judgment	OK	OK

Table 17 Optimal designs of truss typed temporary structure for 4 lanes

Classification	STK500	UL-700
External diameter	48.6 mm	48.6 mm
Thickness	5.3 mm	3.8 mm
Ratio	0.968 < 1.0	0.913 < 1.0
Judgment	OK	OK

Φ48.6×1.8_UL700, based on the 2-lane system, but as the span increased, the members' load increased. Thus, the members should have the capacity to bear the deflection and stress concentration.

Fig. 15 shows curves of load and displacement by using STK500 (Φ48.6×2.3) and UL-700 (Φ48.6×1.8) in case lane 2 and 2 layers. As can be seen, STK500 is 0.5 mm thicker than UL-700 so that it is a bit more suitable than UL-700 in terms of initial strength. But, UL-700 showed three times higher ductility than STK500 and its maximum bearing capacity is also two times higher than that of STK500.

5. Conclusions

This study presents an innovative space truss frame used to maintenance and LCC control constructions of road tunnels, which has a significant merit to carries out maintenance construction of tunnels without blocking cars and transportations. The final conceptual structure for maintenance is shown in Fig. 16.

Its structural behaviors are investigated through analytical method using MIDAS commercial software program. Finally appropriate truss typed temporary structures are designed by using structural analysis results. The following are the conclusions based on the analysis results of member systems in this temporary structure. The following Tables 15, 16, and 17 are the optimal designs of the external diameter and thickness for each steel type (based on 2, 3, and 4 layers).

Acknowledgments

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References

Ahrari, A. and Atai, A.A. (2013), "Fully stressed design evolution strategy for shape and size optimization of truss structures", *Comput. Struct.*, **123**, 58-67.

Jiang, A. and Wang, J.Y. (2012), "Research of intelligent displacement back analysis of Dalian subway tunnel excavation disaster prediction", *Disaster Adv.*, **5**(4), 1096-1103.

Asakura, T. and Kojima, Y. (2003), "Tunnel maintenance in Japan", *Tunn. Undergr. Space Technol.*, **18**(2), 161-169.

Cui, Y.L., Wu, W. and Tang, D.H. (2011), "Application research on TRIZ physical contradiction solving principles in armored vehicles", *Adv. Mater. Res.*, **308**, 380-383.

Degertekin, S.O. and Hayalioglu, M.S. (2013), "Sizing truss structures using teaching-learning-based optimization", *Comput. Struct.*, **119**, 177-188.

Elena, K. (2007), "Bases of quality management of construction and repair of highways", *Baltic J. Road Bridge Eng.*, **2**(3), 101-109.

IBC 2009 (2009), International Building Code (IBC); International Code Council, Inc.

John, V.R. (2006), "Maintenance of road structures", Technical Report; INDEVELOPMENT.

KBC 2009 (2009), Korea Building code 2009; Architectural Institute of Korea.

Kim, S.W. (2010), "New ultra light steel pipe scaffolds commercialized", *Korea Metal J.* http://eng.kmj.co.kr/news/articleList.html

Lee, B.H. (1998), *Maintenance of Road Tunnel*, Won-Ki-Sool.

Lee, D. and Shin, S. (2014), "Advanced high strength steel tube diagrid using TRIZ and nonlinear pushover analysis", *J. Constr. Steel Res.*, **96**, 151-158.

Lee, D. and Shin, S. (2015a), "High tensile UL700 frame module with adjustable control of length and angle", *J. Constr. Steel Res.*, **106**, 246-257.

Lee, D. and Shin, S. (2015b), "Nonlinear pushover analysis of concrete column reinforced by multi-layered, high strength steel UL700 plates", *Eng. Struct.*, **90**, 1-14.

Lee, D.K., Kim, D.H. and Kim, J.H. (2012), "Structural and functional measurements of a space truss frame for maintenance works in tunnels", *Korea Inst. Struct. Maint. Inspection*, **16**(3), 92-98.

Lee, D., Kim, D., Lee, J., Noh, P. and Park, S. (2015), "Analytical testing and evaluation of truss typed structures for tunnel maintenance", *Smart Struct. Syst., Int. J.*, **15**(4), 949-961.

Lee, D., Kim, Y., Shin, S. and Lee, J. (2016), "Real-time response assessment in steel frame remodeling using position-adjustment drift-curve formulations", *Automat. Constr.*, **62**, 57-65.

MIDAS (2012), MIDAS GEN Manual; MIDAS IT.

Ministry of land (2010), Transport and Maritime Affairs, Statistics of Road bridges and tunnels.

Norwegian Public Roads Administration (2004), Standard Road Tunnels, Statens vegvesen.

World Road Association (2010), Road Tunnel Manual - Operation and Maintenance, PLARC.

Sato, M., Kobayasi, A. and Mori, E. (1996), "Automated maintenance robot for expressway-tunnel", *Proceedings of the 13th ISARC*, Tokyo, Japan, June, pp. 271-278.

Sofla, A.Y.N., Elzey, D.M. and Wadley, H.N.G. (2009), "Shape

morphing hinged truss structures", *Smart Mater. Struct.*, **18**(6), 1-8.
Terato, H., Yokozawa, K., Inagawa, Y., Miura, Y. and Takemoto, N. (2008), "Development of a work carriage for tunnel maintenance", *Proceedings of the International Symposium on Life-Cycle Engineering*, Lake Como, Italy, June, pp. 661-666.
World Road Association (2010), Road Tunnel Manual, PLARC.

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