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Analytical testing and evaluation of truss typed structures for tunnel maintenance

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Abstract. The goal of this study is to present numerical modeling and analytical testing in order to evaluate an innovative space truss typed temporary structure, which is used to maintenance and repair of road tunnels. The present space truss structure has merits to use UL-700 high strength steel tube as members and to carry out maintenance and repair works of road tunnels without blocking cars and transportations. Numerical modeling and analytical testing of the space truss are investigated by using commercial engineering software, i.e., ABAQUS 6.5-1, and then it is verified that the truss structure has both structural safety and effective function for maintenances and repairs of road tunnels.

Keywords: road tunnel; maintenance; repair; space truss temporary structure; numerical modelling; analytical testing

1. Introduction

Until now, road tunnel is reportedly extended to 2,008 km altogether in republic of Korea under the number of 1,382 (Ministry of land, Transport and Maritime Affairs 2010) as shown in Fig. 1. As can be seen, it would be gradually important to devise rational and specific ways (Terato *et al.* 2008) for increasing maintenance of existing road tunnels than to build new road tunnels for human's convenience.

Maintenance works of road tunnels (Sato *et al.* 1996, Asakura 2003, Wang *et al.* 2007) and bridges (Hoult *et al.* 2008) classified with inspection, investigation, measure, reinforcement, and cleaning, which diversely occur over two or three times pro tunnel (Lee 1998) per year for life cycle control. Therefore the increasing demand on effective and economical maintenance of existing road tunnels including recently completed tunnels would be a new trend of maintenance industries of structures, apart from building new road tunnels. Classical maintenance (World Road Association 2010, Norwegian Public Roads Administration 2004) of road tunnels is carried out by using specific equipments such as TC lifts, scaffolds, and moving trucks. During maintenance

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construction, some lane of road tunnels is blocked and then vehicles cannot move the blocked lanes. The partial or full traffic blockade provides poor transportation such as traffic jam.

In order to overcome the problems of the typical maintenance method (John 2006) of road tunnels, a specific space truss typed temporary structure was introduced by Lee *et al.* (2012). Since it only moves inside of a so-called limited building line (World Road Association 2010), maintenance works can be favorably progressed without obstructing vehicular traffic.

In this study, structural analyses are carried out and investigated to obtain appropriate design results of the space truss (Lee *et al.* 2010) typed temporary structure. The appropriate designs have to be satisfied with all functional, safe, and economic aspects. The design results depend on given diverse design conditions such as sizes of 2, 3, 4 lane road tunnels, truss materials, and cross-section of truss members, and 2, 3, 4 layered space truss typed temporary structures.

This study is divided into 4 sections. In section 2, tunnel space frames are modeled as alternative to overcome above-mentioned problems of the typical maintenance methods. Numerical examples to verify structural behaviors of the present space truss frames are studied, carrying out structural analyses by using ABAQUS commercial program in section 3, and the conclusions are presented in section 4.

2. Necessity of improving road tunnel maintenance processes

The existing road tunnel maintenance methods (World Road Association 2010) result in partially or fully blocking road lanes in tunnel in order to occupy fields of maintenance constructions. Especially, maintenance works of tunnels cannot be carried out during rush hour because it may aggravate the existing traffic jam, as shown in Fig. 1.

Table 1 shows number of road tunnels, in which maintenance is required periodically in Korea. Here 1 type denotes road tunnels over 3 lanes in size and 1 km in length. Type 2 denotes road tunnels except for type 1. As can be seen, the significance of efficient maintenance is increasing. Actually a national budget of 200 million dollar (Korea Infrastructure Safety and Technology Corporation, 2011) was paid to maintenance of road tunnels in Korea in 2011.

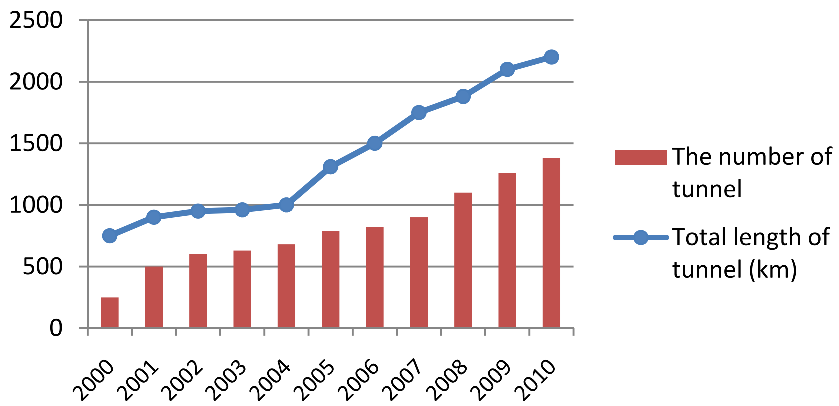


Fig. 1 The total length and number of road tunnel in republic of Korea

(a) Traffic jam (b) Existing maintenance method

Fig. 2 Problematic of existing maintenance method of road tunnels

Table 1 Statics of road tunnels for maintenance in Korea

	Number of tunnel	Total distance (km)
Total quantity	1,448	1,099,137.80
1 type for maintenance	477	610,673.20
2 type for maintenance	971	488,464.60

3. New apparatus for tunnel maintenance works

Fig. 2 presents components of a road tunnel, including construction limit lines, i.e., limited building line, dust stripe, drainage holes, and lateral clearance.

In order to improve this maintenance process of road tunnel, a specific temporary space frame which only moves inside of a so-called limited building line (World Road Association 2010, Norwegian Public Roads Administration 2004) is presented in this study. In addition, the temporary space frame has to be easily assembled and disjointed by workmanship during maintenance periods of road tunnels, and then its economical and optimized structural type is truss (Chilton 2000, Bigoni *et al*. 2012).

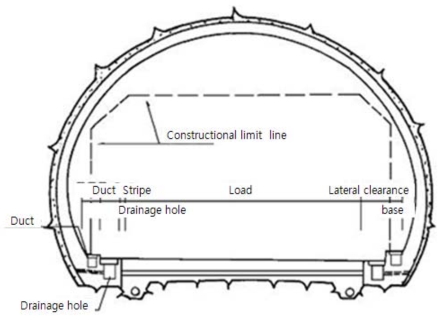


Fig. 3 Components of a road tunnel

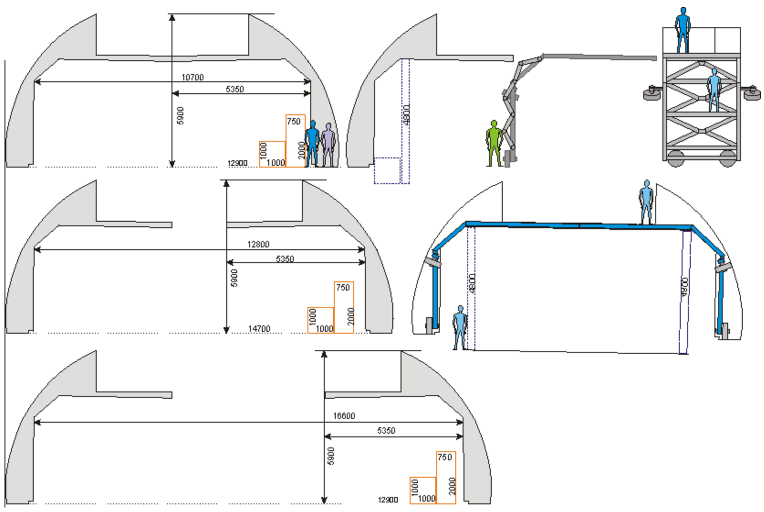
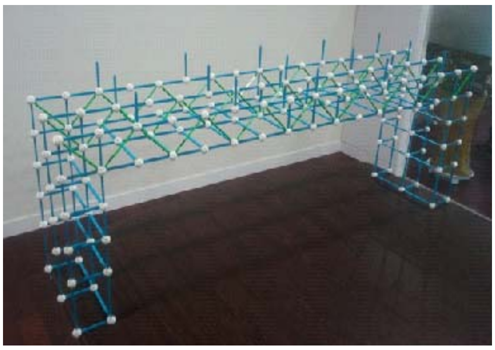


Fig. 4 A simple frame type and limited building lines

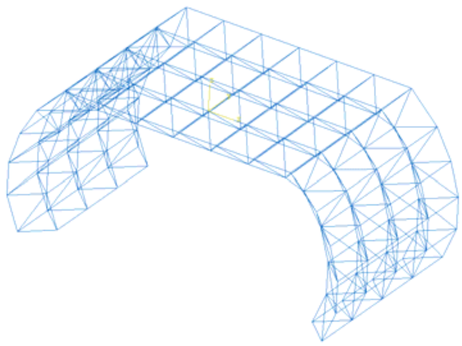
According to satisfying with these conditions, diverse alternative can be generated as can be seen in Figs. 3 and Fig. 4. In Fig. 3, gray areas are outside of space enclosed by limited building lines, 12.9 m (width) x 4.8 m (height) in 2 lane tunnel, 14.7 m x 4.8 m in 3 lane, and 16.6 m x 4.8 m in 4 lane.

For evaluated temporary frames, a simple frame type in Fig. 3 which consists of some thick steel pipe and a space truss type in Fig. 4 which consists of many thin steel pipes are presented in this study. The evaluated temporary frames can be only inserted and operated in these gray areas.

In this study, space truss frame types are decided to be an appropriate structure for maintenance (Sadek and Hamad 2007) of road tunnels, because space truss members are small and light steel pipes and then the characteristic results in superior workmanship. In especial, Fig. 4(b) is intensively investigated in this study, since curved shapes lead to make workers easily arrive to surface of tunnels. In addition, it is standard and simple for control since it is not actuated system (Osterhuit and Biloria 2008, 2006).



(a) Space truss frame with sharp corners



(b) Space truss frame with curved corners

Fig. 5 Space truss frame types

4. Tunnel space frame analysis

4.1 Design overview and applied load

An appropriate evaluated temporary space truss system is sketched in Fig. 4(b). This temporary system, i.e., space frame, was analyzed with ABAQUS 6.5-1 (Venkatesh 2011), a general-purpose nonlinear analysis program. The analysis aims to evaluate the bearing capacity (push-over to constant vertical load) of each steel type and material in each system, comparing the quantity of the temporary construction materials.

Table 2 shows the change in the quantity of materials for the 2-layer system. As the number of layers increases by 1, the quantity of the temporary construction materials increases by about 330 kgf.

4.2 Procedure of nonlinear analysis

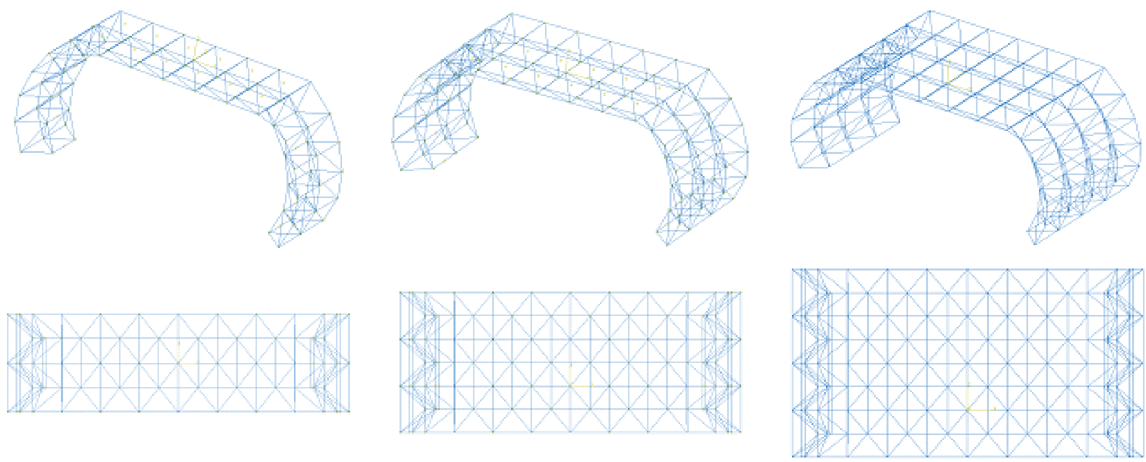
4.2.1 Modeling data

This temporary system (Ramaswamy 2002) is modeled, based on the 2-lane system in a tunnel. This 10.7 m-wide and 4.8 m-high system is designed within the limited building line as shown in Fig. 3 considering the interference of finishing and equipment.

Fig. 5 shows the analysis modeling and systems of a different number of layers.

Table 2 Change in the quantity of materials for 2-, 3-, and 4-layer system

Classification	2 Layers	3 Layers	4 Layers
DL (Based on Ø48.6 x 1.8)	660kgf	995kgf	1,325kgf
LL	117kgf/m^2		



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

Fig. 6 Analysis Modeling

4.2.2 Loading range

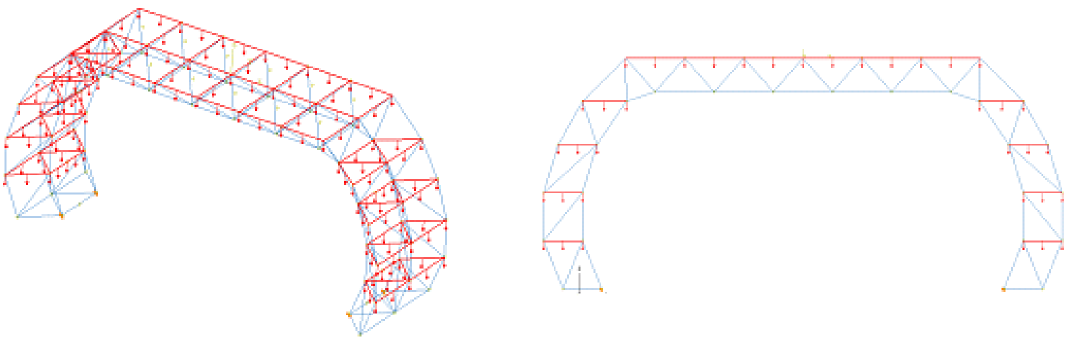
As shown in Fig. 6, the beam load is put on each framework member in the vertical direction (Z-dir). Push-over was analyzed until the members reached yield strength.

4.2.3 Reaction point

Fig. 7 shows the reaction points. Y-dir is a roller action in consideration of the movement of materials in the tunnel and the reaction of the temporary construction material is formed at 4 reaction force points.

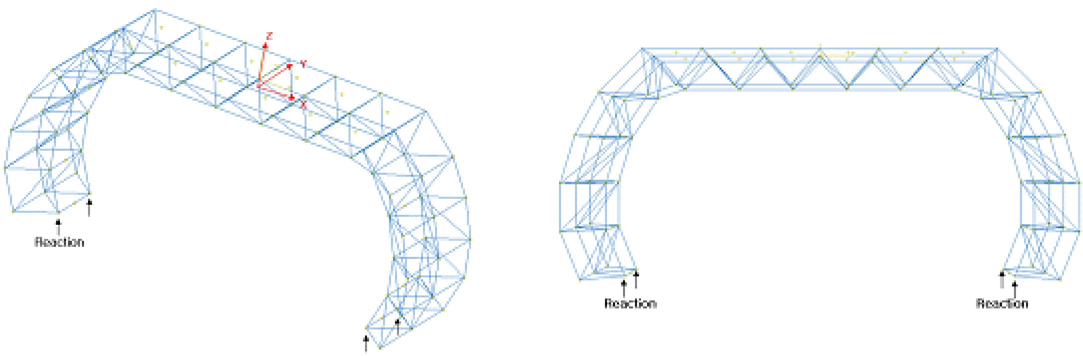
4.3 Results of nonlinear analysis

As shown in Fig. 8, the push-over analysis result shows that the maximum stress was measured at the legs of both sides and members cracked due to compressive buckling. Thus, the reinforced wall thickness of the inside pipe and its strength need to be increased.



(a) Iso view (b) Front view

Fig. 7 Loading Range



(a) Iso view (b) Front view

Fig. 8 Location of Reaction Points

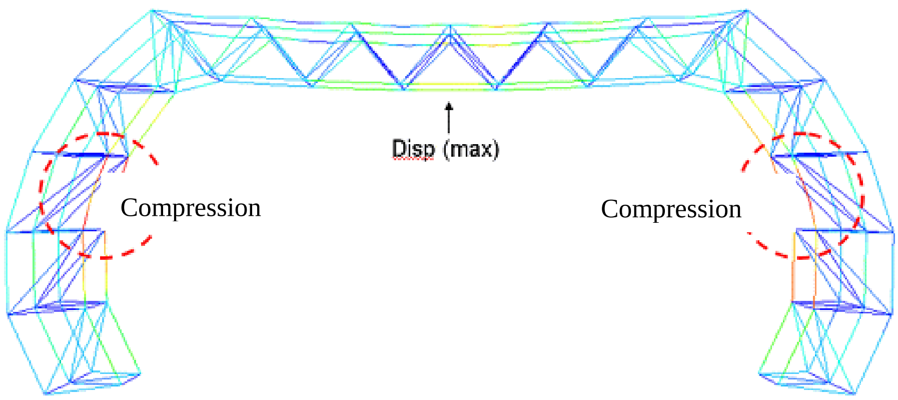


Fig. 9 Analysis Results

4.3.1 Comparison between STK500 and UL-700

Table 3 compares two types of steel: UL-700 and STK500 and the results of the comparison are depicted in the following Fig. 9.

Table 3 Comparison between STK500 and UL-700

Classification	STK500	UL-700
Size of Member	Ø48.6 x 2.3	Ø48.6 x 1.8
Yield Strength (MPa)	325	595
Unit Weight (kg/m)	2.63	2.08
Quantity (kg/frame)	299	237

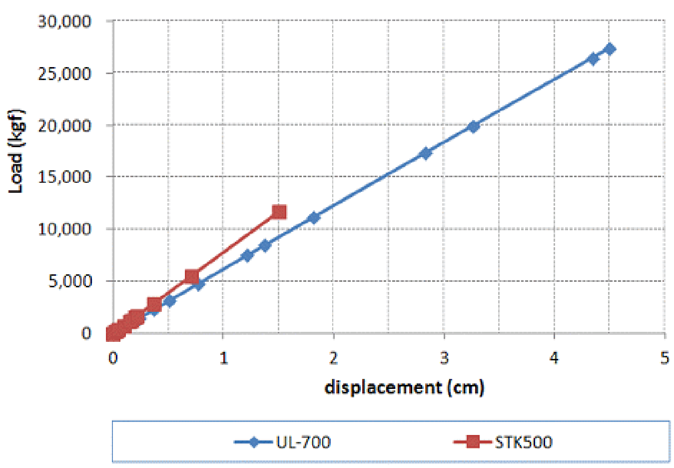


Fig. 10 Comparison between STK500 and UL-700

As can be seen in Fig. 9, 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.

4.3.2 Performance comparison of different diameters

Table 4 compares pipes with two different thicknesses: 1.8 mm and 2.3 mm, with diameters of the analyzed pipes ranging from 19.1 mm to 48.6 mm. Fig. 10 shows the results.

Analysis results indicate that the initial bearing capacity of the 1.8 mm-thick pipe increased proportionally to the increase of its diameter, and a bearing capacity exceeding the factored load was secured in the cases of Ø30x.18, and Ø48.6x.18. In the Ø40 system, the stress was concentrated highly on the system’s leg parts. Thus, this entire system is unsuitable in terms of ductility and bearing capacity.

Fig. 11 depicts the performance comparison of the 2.3 mm-thick pipe. The bearing capacity of the pipe varied depending on the thickness and the external diameter. The Ø48.6-diameter system showed stable movement in terms of bearing capacity and ductility.

4.3.3 Performance comparison of different thicknesses

Table 5 compares the -48.6 diameter-steel pipes in different thicknesses. Fig. 12 shows the results.

As can be seen in Fig. 12, the results of different thicknesses for bearing capacity indicate it increases by 10~16tonf as the thickness increases by 0.5 mm. As for the 2.8 mm-thick pipe, the stress is concentrated at its leg parts and its bearing capacity falls far short of the required value.

Table 4 Performance comparison of different diameters

Classification		UL-700			
Diameter	1.8T	Ø19.1	Ø30.0	Ø40.0	Ø48.6
	2.3T	Ø19.1	Ø30.0	Ø40.0	Ø48.6

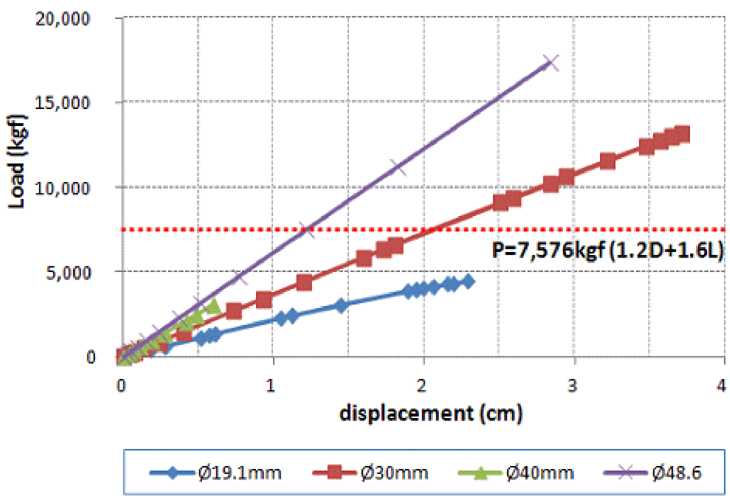


Fig. 11 Performance Comparison of Different Diameters (T=1.8 mm)

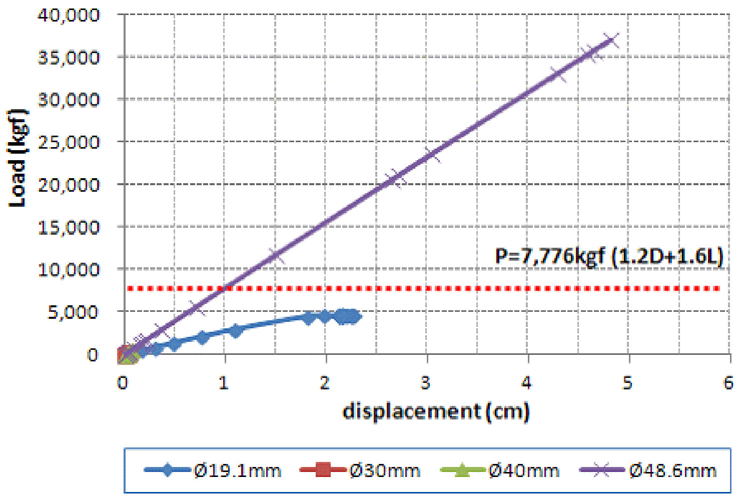


Fig. 12 Performance Comparison of Different Diameters (T=2.3mm)

Table 5 Performance comparison of different thicknesses

Classification	UL-700 (Ø48.6)			
Thickness of Member (mm)	1.8	2.3	2.8	3.3

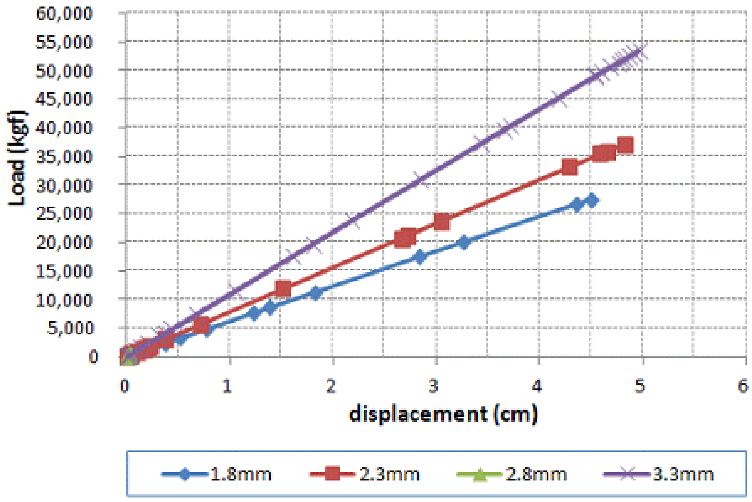


Fig. 13 Performance Comparison of Different Thicknesses (Ø48.6)

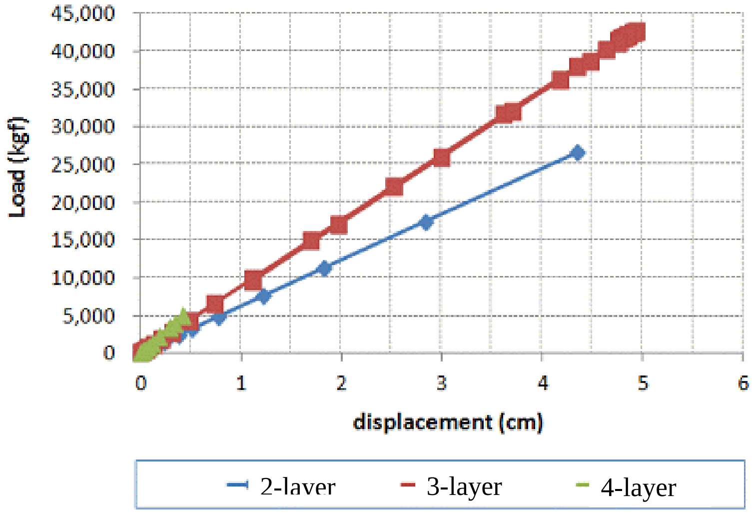


Fig. 14 Performance Comparison of a Different Number of Layers (Ø 48.6 x 1.8_UL-700)

4.3.4 Performance comparison of a different number of layers

As can be seen in Fig. 13, the results of the comparison indicate that the 2-layer and the 3-layer temporary system showed higher bearing capacity and ductility than the 4-layer system.

5. Conclusions

This study presents numerical modeling and analytical testing of an innovative space truss typed temporary structures which can be used to maintenance works of road tunnels.

According to numerical investigations by using ABAQUS, appropriate design results of space truss structures satisfying both economical aspect and structural safety are verified under the conditions that steel material, size of truss members, and shape of apparatus are assumed to be design parameters in this study.

The conclusions of the nonlinear analysis on this temporary system are:

Table 6 Results of the nonlinear analysis

Classification		Ø48.6 x 2.3(STK500)	Ø30 x 1.8(UL-700)	Increase and/or Reduction
Maximum Bearing Capacity (tonf)		12.5	13	
Quantity (kgf)	2 Layers	834	397	437kgf Reduced
	3 Layers	1,255	598	657kgf Reduced

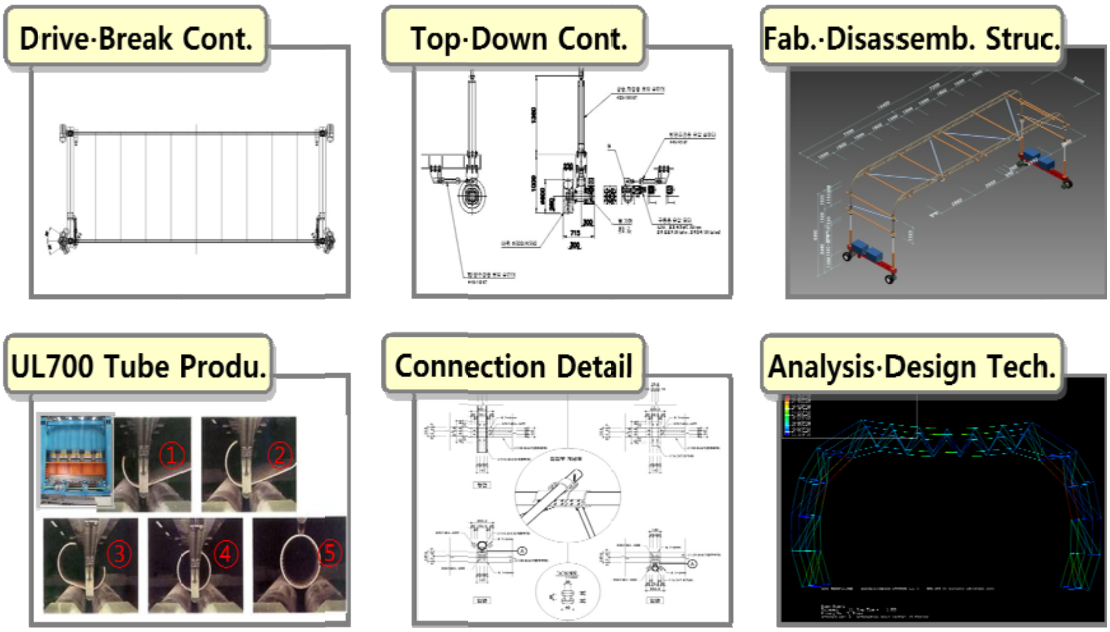


Fig. 15 Six Core Technologies for evaluating the present Conceptual Model

The temporary system results indicate that a higher bearing capacity must be secured than the capacity required for the factored load, and Ø30 x 1.8(UL-700) is expected to save 50% of material quantity consumed in Ø48.6 x 2.3(STK500) for the 2-layer and 3-layer systems.

In the future, the present conceptual model for efficient maintenance of road tunnels will be evaluated and completed with respect to six core technologies including analysis design technology which is treated in this study, as shown in Fig. 14.

Six core technologies are classified with the driving-breaking control of truss structures, the top-down control of truss structures, the fabrication-disassemble control of truss structures, the production method of high-strength steel tube members, the safe connection detail of members, and the effective computational analysis method. Note that they can be treated in the field of overall engineering, not a specific engineering. For example, the first and second technologies are related to mechanical engineering. The third and fourth technologies are linked to manufacture engineering. In details, strong stiffness of UL700 steel may result in difficulties in tube production, and therefore a specific manufacture method such as press bending method must be considered in the future study.

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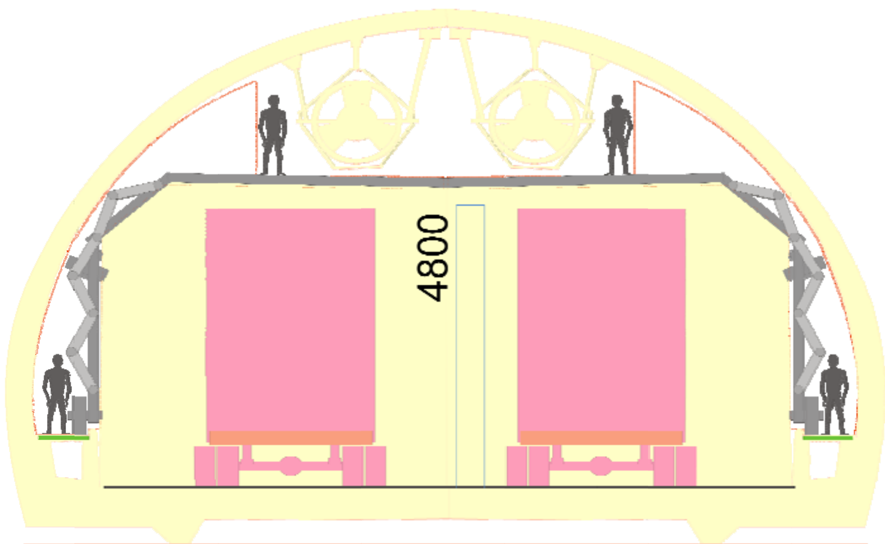
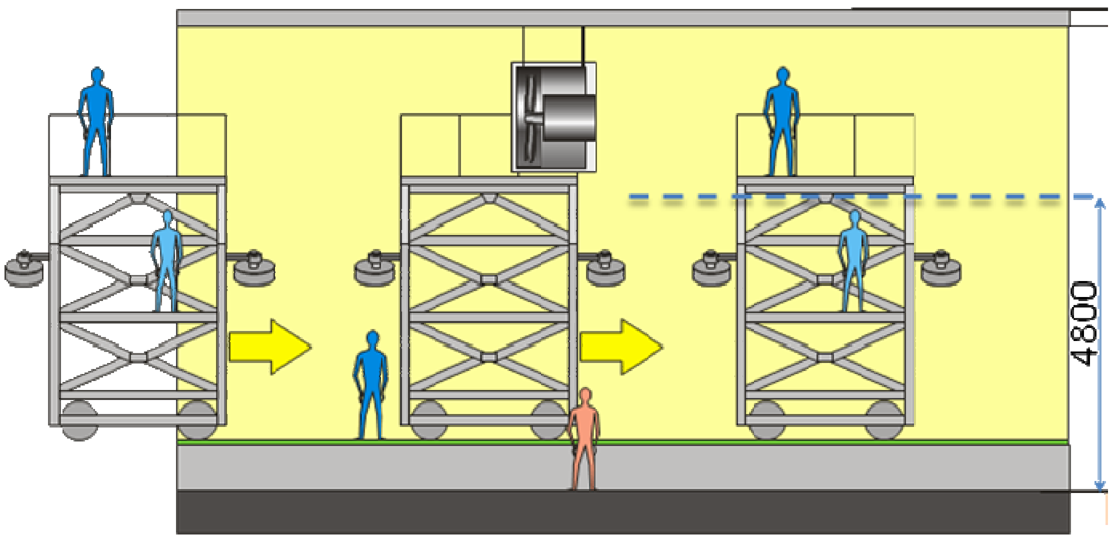
Appendix. A

The promising ideal situation simplifying the present temporary space truss system is sketched in Fig. 16, weighing both workability of maintenance and movement of vehicles. Due to not determining concrete design model for the smart structures, it would be improved by 6 core technologies as shown in Fig. 15 in the future's study.



(a) Front view in ideal situation for workers and cars



(b)Side view in ideal situation for workers and cars

Fig. 16 Descriptions of ideal situation simplified for workers and vehicles