Field Load Testing of the First Vehicular Timber Bridge in Korea

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Summary

The first timber bridge for vehicles in Korea, a single-span, arched truss bridge 30m in length, was constructed in 2012. The bridge was designed and constructed as a part of national research projects for the development large timber structures funded by the Korea Forest Research Institute. This paper briefly introduces the development process of the bridge including design specifications, member tests, full-scale loading tests and finite element analysis. It then presents the results of the first in-situ truck load tests for the bridge. The tests are performed as an initiation of multiple-year monitoring project for performance assessment. Both static and dynamic responses such as deflection, mode frequency, and strains of major members are measured and compared to the analysis results of the design step.

Keywords: Vehicular timber bridge, Field loading test, Laboratory test, Finite element analysis.

1. Introduction

Timber's strength, light weight, and eco-friendly properties furnish features that are desirable for bridge construction, and they also present a natural and aesthetically pleasing appearance, particularly in natural surroundings. Due to these superior characteristics of timber as a bridge material, they have been used as main members of vehicular bridges in Europe and United States.

In Korea, however, timber has not been used as main member of vehicular bridges although the use of timber as a main structural member has been increasing for other structures such as pedestrian bridges and buildings. In an effort to apply timber to bridge construction, the Korean Forest Research Institute initiated a research project for the design and construction of vehicular timber bridge and the establishment of design specifications. As an output, a vehicular timber bridge was built successfully for the first time. This paper summarizes the research activities for the vehicular timber bridge in Korea, and the results of performance evaluation tests in the laboratory are briefly introduced. Finally field load tests and the results were presented.

2. Researches and development for vehicular timber bridge in Korea

In 2009, the Korean Forest Research Institute launched a research project for the design of a timber bridge. It started as the development of a bridge deck floor 30m in length. In this design, glue laminated timber (glulam) was used because it can be manufactured in a wide range of shapes, which is appropriate for the construction of a bridge deck floor with a relatively long span. In this research, the pre-stressed glulam deck floor system was designed based on the design guideline by USDA [1]. The required level of pre-stressing and design assumptions such as symmetric behaviour and non-separation at laminated faces were identified and verified.

Following the development of the pre-stressed glulam deck system, research on girder bridges was initiated in 2010. Girder bridges with two lanes and 25, 30 and 35m in length were developed. A sawn lumber deck floor system was adopted for the girder bridge, which was designed with a series of rectangular panels and was supported by 5 main girders. A design and analysis program for the girder bridge was developed and the design procedure was established. The structural behaviours of the bridge design were verified numerically through detailed 3D finite element analyses.

Based on the previous research, comprehensive research for the first vehicular timber bridge in Korea was started in 2011. The research project included the whole process including design, manufacturing, laboratory test, field test, and the construction of the bridge. Among the various bridge types, an arched truss structure was selected for a 30m single-span bridge due to the advantages of structural efficiency and aesthetic value (Fig. 1).

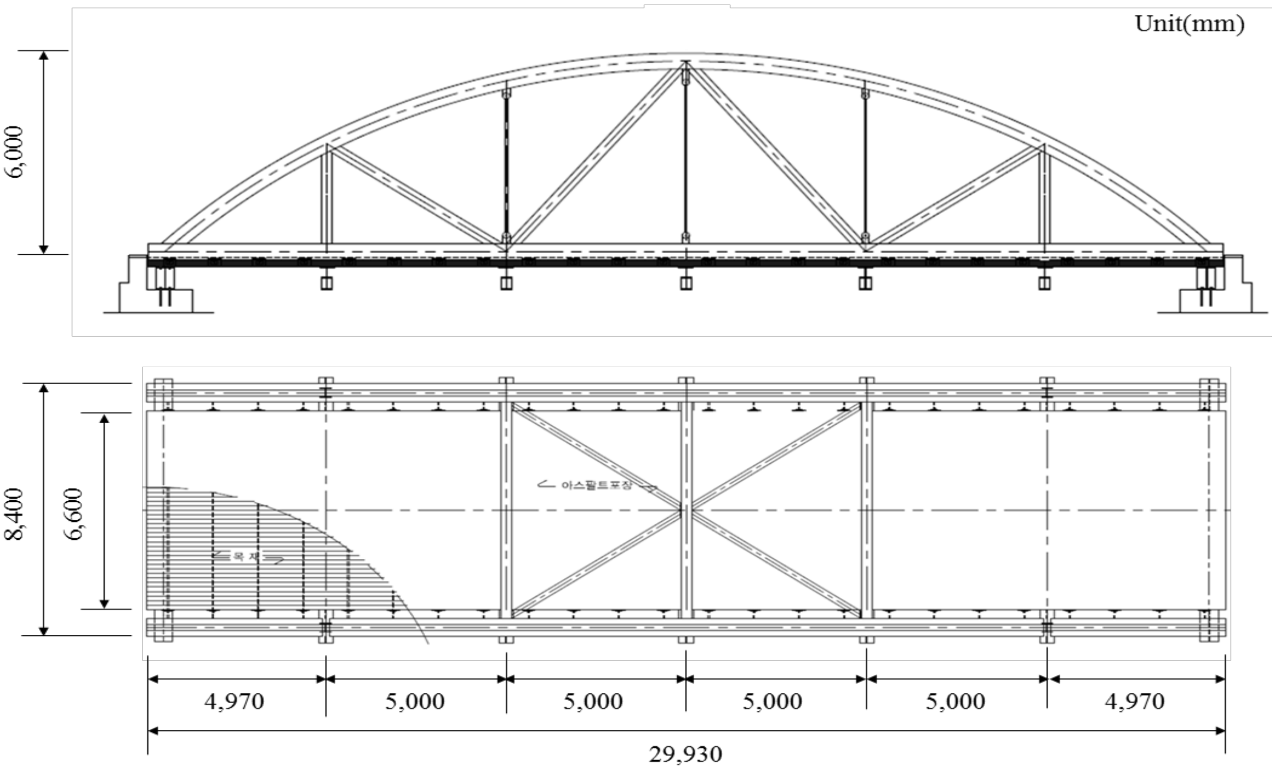


Fig. 1 Longitudinal section and floor plan of bridge designed in 2011 (Named Hanareum bridge later)

The main members of the arched truss were made of glulam, and dowel-type joints are used to connect the main members. The vertical members of truss, cross beams, pre-stressing elements, dowel plates and components to assemble were made of steel while the other main members are all made of wood. For the glulam deck system, stressed-laminated system, which was researched in previous studies, was chosen, due to the advantages of prefabrication, installation, and maintenance. A total of 5 cross beams were laid beneath the deck at the intervals of 5m to support the deck floor and to transfer the load from the floor to the truss members. An additional two cross beams were also installed to seat the bridge on the abutments. A number of codes, specifications and guidelines [2-6] were used to design the truss, joints and other detailed parts of the bridge and the allowable stress design method was applied. For the material of the main glulam members, pitch pine was chosen because it is one of the most common species of trees in Korea, would be predicted to provide cost-effectiveness for the bridge. Korean Industrial Standard provides the mechanical properties of symmetric laminated pitch pine timber as shown in Table 1, classified according to grade of strength. Among them, 10S-30B grade materials were selected for the bridge.

Table. 1 Mechanical properties of symmetric laminated pitch pine timber(KS F 3021)

Grade of strength	Allowable Stress(MPa)				Modulus of elasticity(MPa)	
	Flexural		Axial		x-x axis	y-y axis
	x-x axis	y-y axis	Tensile	Compressive		
12S-37B	12.0	8.0	8.0	10.0	11,000	10,000
12S-33B	11.0	7.5	7.0	8.0	10,000	9,000
10S-30B	10.0	7.0	6.5	7.5	9,000	8,000
9S-27B	9.0	6.0	6.0	7.0	8,000	7,000

Using the above research, an arched truss timber bridge for vehicle was completely manufactured and tested in the laboratory before being constructed at the field. The next chapter presents the laboratory tests and corresponding results.

3. Full scale performance evaluation test in laboratory

In order to ensure the performance of members, joints and the entire bridge system, a series of full scale test was performed at Hybrid Structural Test Centre of Myongji University in 2011. The tests for glulam members consist of the bending, tensile and compression strength test, and static loading and fatigue loading tests were performed for the arch truss bridge [7].

In tests of the dowel-type joint connections, one of the most complex parts in timber structure design, structural performance and failure behaviour were verified by both a finite element analysis and experiments. Full scale test specimens for diagonal members and lower chord were manufactured to have same details as the connections of the bridge so as to assess whether the strength satisfies required level.

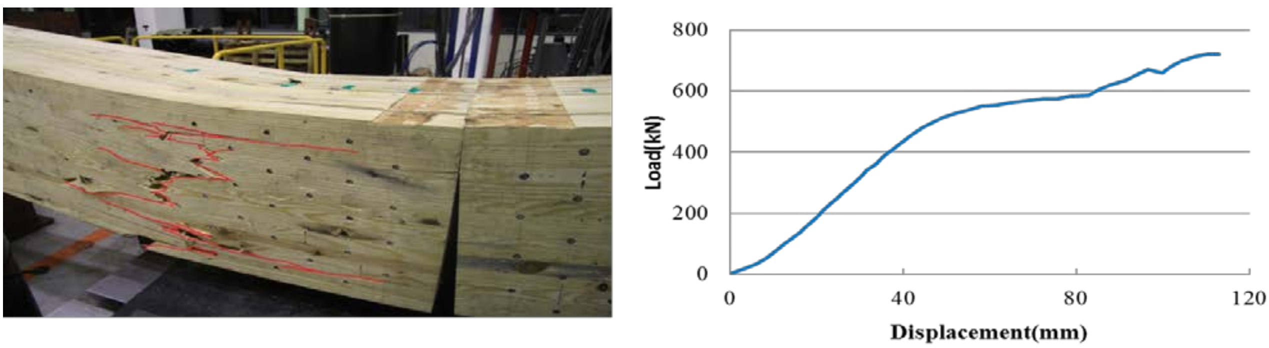


Fig 2. Flexural strength tests on the lower chord

As a result, the maximum stresses of members were expected to be from 80% to 95% of the allowable axial stress. In flexural tests on the lower chord, it was found that the strength of the connected joints were sufficiently high such that maximum tensile stress of the connection is higher than the non-joint part of the member by 78%, due to the superior flexural strength of the steel dowel plate. Overall, the average axial strength, flexural strength and ductility were also at satisfactory levels.

The entire bridge span including arched truss, deck plates and cross beams was assembled in the structural test laboratory for static and dynamic loading tests (Fig. 3). The main objective of this full scale loading test was to verify whether the assembled bridge system behaves as designed. More specifically, the linearity for load-deflection relationship and the symmetry of deformed shape were investigated through a 384kN static loading case which is 90% of the design truck load. Test results showed that the resulting member forces were quite small compared with design values especially for timber, and the symmetric condition of whole bridge was well satisfied to meet well with the difference of deflection less than1mm. The maximum deflection of truss, cross beams and deck floor were also found to be smaller than design values.

Fig. 3 Static load testing in laboratory

In fatigue tests, cyclic loadings up to 50kN were applied. A total of 80,000 cycles were loaded throughout the test. It was found that there was no problem on the integrity of joints and members other than the slight increase in the center deflection was observed after the test. This deflection seemed to be caused by the relaxation of pre-stressing or the separation of joint connection occurred during the cyclic loadings.

4. Field load testing

4.1 Construction of the bridge

After the laboratory testing, the bridge was disassembled for transport and reassembled at the construction site. The construction field was located at a forest road of the Micheongol recreational forest, an eastern mountainous region near Yangyang city, Korea. After the installation of a fence and asphalt pavement, the construction of the entire bridge was completed by December 2012, and has been open to the traffic since the official opening ceremony that was held in April 19, 2013.

This bridge, given the official name of 'Hanareum bridge', is 30m in length, 8.4m in width and has a maximum load capacity of 110t. As the first vehicular timber bridge in Korea, Hanareum bridge is expected to serve as the groundwork for the construction of many more timber bridges in the future and establishment of Korean design specifications for timber bridges.

In order for that to occur, it is important to assess the present performance of bridge and to apprehend the long-term behaviour like loosen pre-stressing, deterioration etc. Furthermore, it is required to examine whether the bridge performs as it was intended. Therefore, field testing including static and dynamic load testing was performed May 10, 2013

Fig. 4 Hanareum bridge

4.2 Configuration of field load testing

The bridge was designed as a two-lane bridge with each lane loaded with a 43.2 ton truck. The loading tests were performed with two gravel loaded 27 ton trucks and corresponding calibration was conducted and the test results were compared to laboratory tests and design values. In order to assess the performance of the bridge and to obtain initial data for investigating its long-term behaviour such as loosen pre-stressing and deterioration, a series of static and dynamic load tests were performed in May, 2013.

The resulting deflections and strains at a series of locations were measured. One of main interests was the integrity of pre-stressed glulam deck. It was assumed that the laminated floor deck would retain its integrity without the separation of the glulam timbers if the deck was pre-stressed properly. In order to verify this assumption of integrity, a total of 13 LVDT's were installed beneath the deck floor to get a detailed shape of deflections in the lateral direction (Fig. 5-(a)). In addition, three more LVDT's were installed across the center cross beam for measuring the mid-span deflection of the bridge (Fig. 5-(b)).

(a) Center cross beam *(b) Deck floor*

Fig. 5 LVDT sensor attachment locations

Strains at important locations were also measured. The locations were identified through finite element analysis, which resulted in a total of 7 locations with the largest strain; 2 of upper chord and 2 of lower chord and 3 of deck floor (Fig. 6). Two accelerometers for identifying natural frequencies were installed at the outer sides of bottom deck floor (Fig. 7).

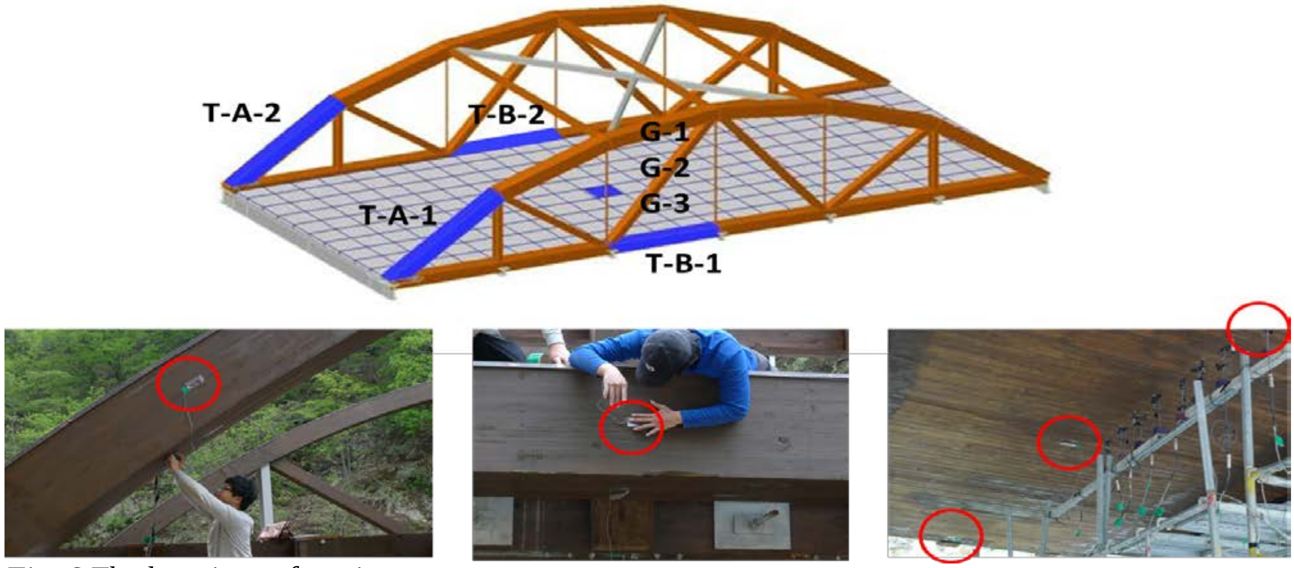


Fig. 6 The locations of strain gauges

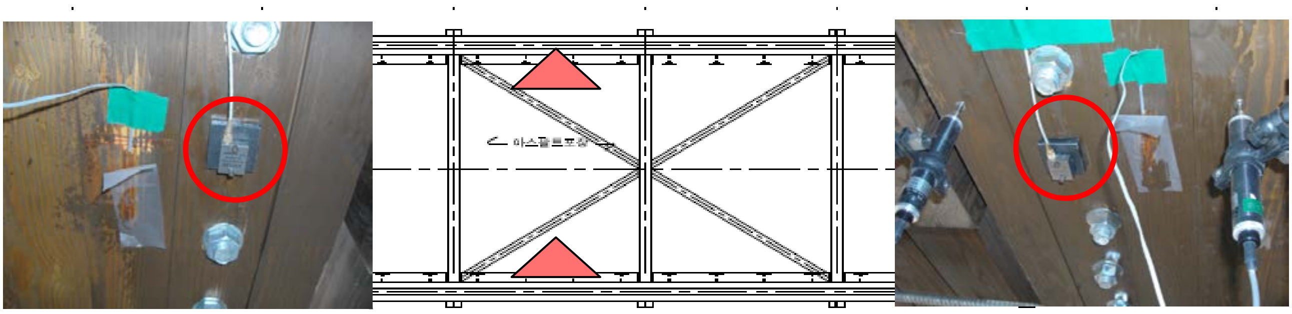


Fig. 7 The locations of accelerometers

In the static loading test, 6 load cases (LC1 - LC6) were set by positioning the truck alone, side by side, and in rows. And in the dynamic loading test, 6 load cases (LC7 - LC12) were set also by letting truck cross the bridge at speeds of 5km/h, 10km/h and 20km/h through each lane (Fig. 8, 9).

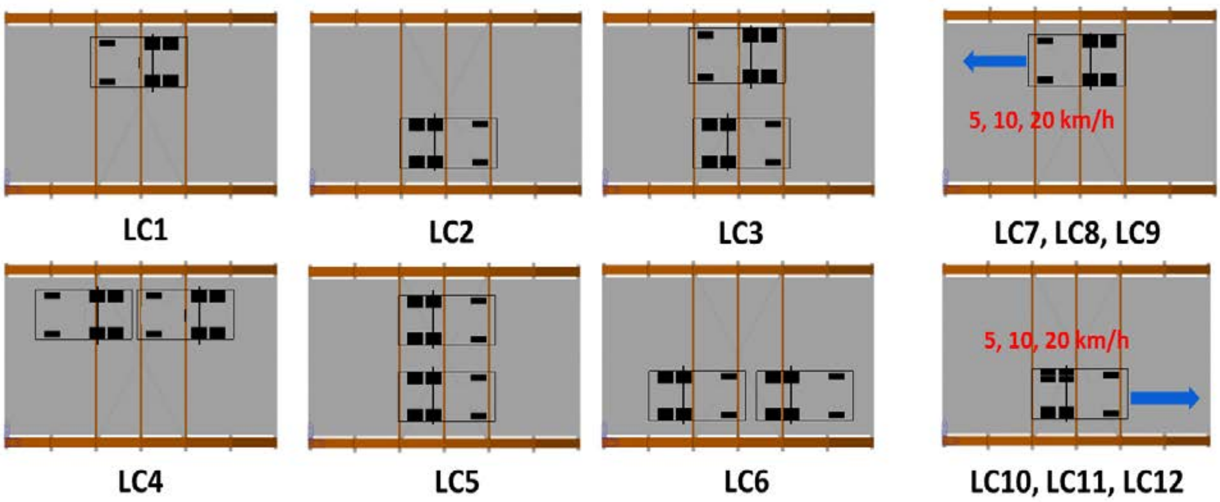
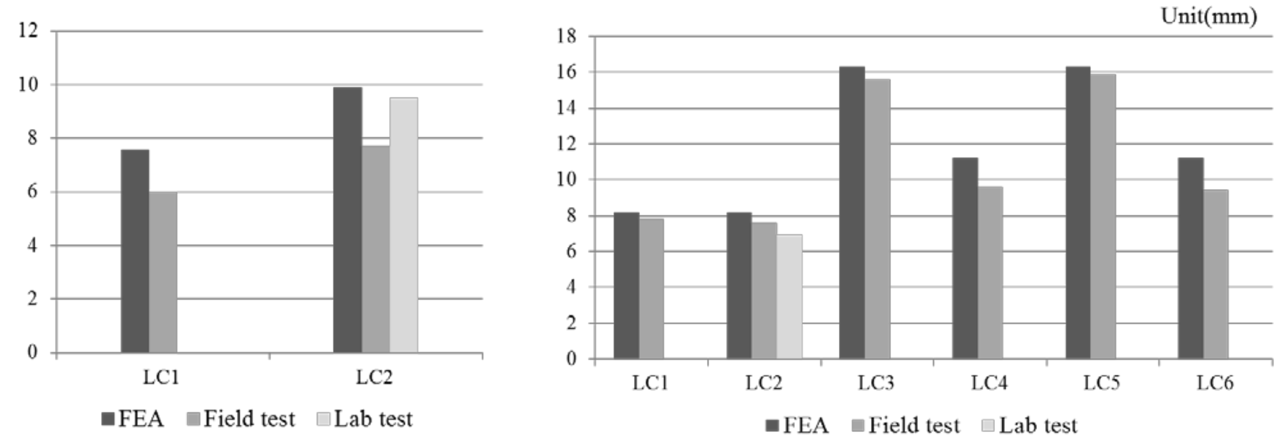


Fig. 8 Load cases for static(LC1-LC6) and dynamic(LC7-LC12) loading test

Fig. 9 Truck loading (left : static test, right : dynamic test)

4.3 Results and Discussions

The results of the static loading tests are plotted in Fig. 10. The displacements of the deck floor and the cross beam at the mid span are compared with their corresponding analysis responses. For a single lane load case, LC2, the results from the laboratory tests were also compared.



(a) Deck Floor *(b) Center cross beam*

Fig. 10 Maximum vertical displacement for static loading cases

As shown in Fig. 10, in general, good consistency was observed between the finite element analysis results and those of the field tests. Larger deflections in the finite element analysis are noted for all the cases, which can be explained by differences in the finite element model and the bridge structure. For example, the connections between timbers were modelled as hinge joints while the bridge has strong connections with dowel plates and bolts which can transfer flexural moment. Furthermore, asphalt pavement and fence, which can strengthen the stiffness of bridge, were not included in the finite element model. This overall stiffness increase is also observed in the comparison of deck floor deflections between laboratory and field test results of LC2.

The purpose of LC3 is to verify the linear behaviour by comparing it with superposition of LC1 and LC2. As shown in Table 2, the load-deflection relationship is found to be linear, and the maximum difference between LC3 and LC1+LC2 is 0.3mm.

Table. 2 Maximum deflections of cross beam for LC1, LC2 and LC3 (mm)

	LC1	LC2	LC1+LC2	LC3
Left	4.3	7.1	11.4	11.1
Middle	7.8	7.7	15.5	15.4
Right	7.3	4.5	11.8	11.9

The symmetry of right and left lanes is investigated by comparing the deflections of the center cross beam for single lane loading case pairs LC1-LC2 and LC4-LC6, which are single truck and double truck loading cases, respectively. A double lane load case of LC5 was also investigated and the test results are shown in Fig. 11, The results indicate that the symmetry of the deflection responses are well maintained, which can be considered to be an indication of the integrity and good quality of the construction of the bridge.

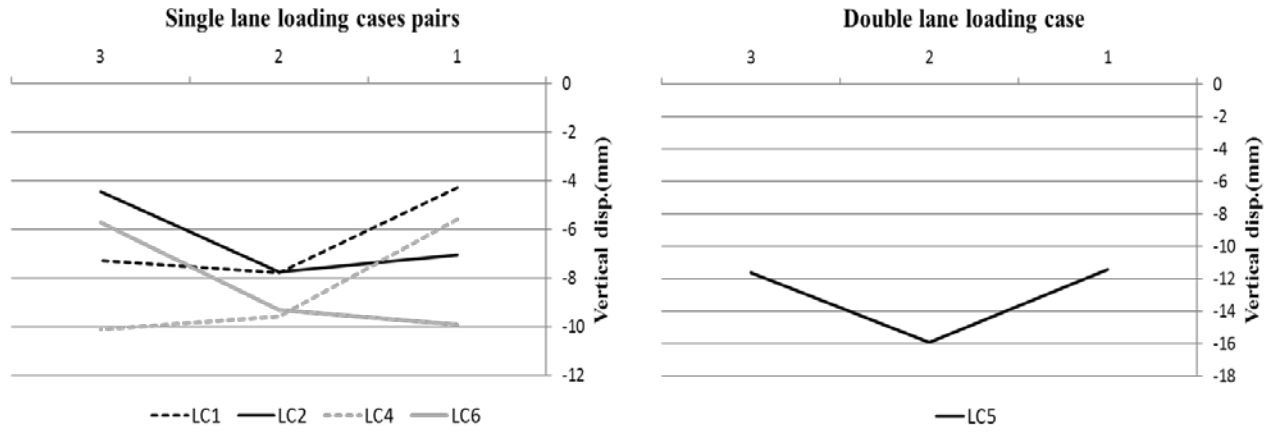


Fig. 11 Deflections of center cross beam for static loading cases

The natural frequencies of the bridge deck were identified from acceleration responses in dynamic loading tests. The first and second mode frequencies were 5.16Hz and 9.06Hz respectively (Fig. 12). Those results will be verified through a refined finite element analysis in further research.

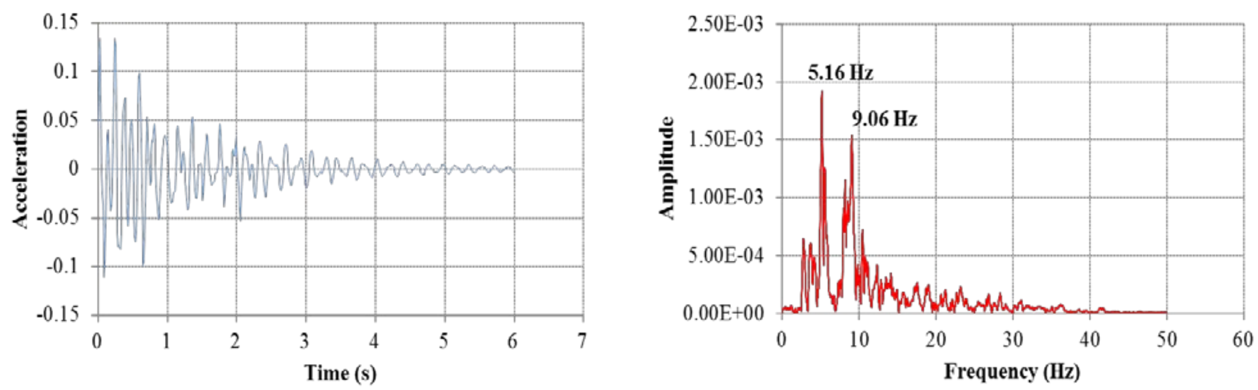


Fig. 12 Acceleration response and its frequency spectrum

In the dynamic loading test, the impact factors were also investigated. The impact factor, defined as the ratio of additional dynamic displacement to corresponding static displacement, depends on the condition of road surface, driving speed, structural characteristics, ratio of live load to dead load, and nature of the response, etc. In this study, for the different speeds of trucks, the maximum vertical displacements of the center cross beam at the crown were measured to calculate the impact factors. The results are depicted in Fig. 13. The largest impact factor was evaluated as 0.198 for 20km/h of the 1st lane. These dynamic test results will be analysed through a further analysis using refined 3D finite element model in a future project.

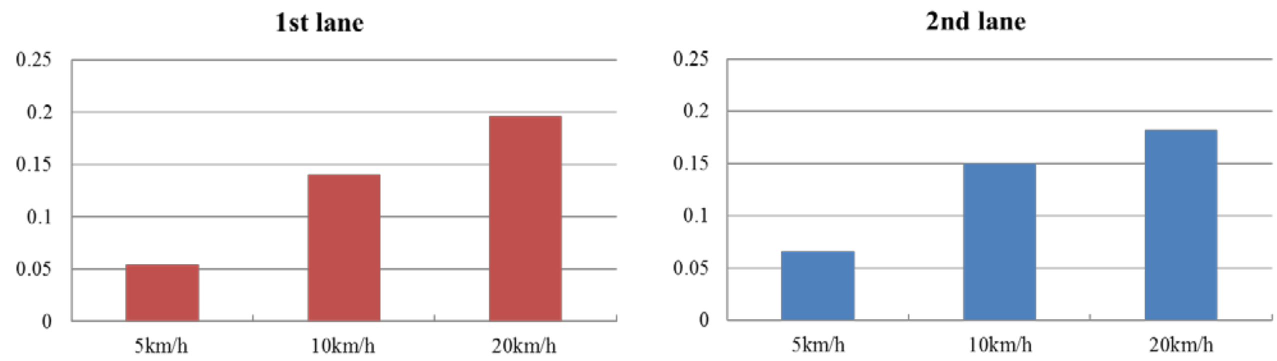


Fig. 13 Impact factors for dynamic load cases

5. Concluding remarks

Recent research and development activities for the construction of the first vehicular timber bridge in Korea are presented. The results of laboratory and field tests indicate that the manufacturing and fabrication quality of timber members is excellent, and that the bridge can perform as designed.

For the further research, a refined 3D finite element model which reflects the current status of the bridge will be established based on the results of the field tests. To investigate the long term behaviour of the bridge, periodic load testing is planned and the finite element model will be updated based on the corresponding results. The updated model will be used to assess current performance and to establish an appropriate maintenance plan for the bridge.

It would be expected that the successful construction of the Hanareum bridge will lead to the development of more vehicular timber bridges in Korea in the future. The development of new design specifications for timber bridges in Korea is also in the planning stages.

Acknowledgements

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