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Characteristics of Static and Dynamic Loading Tests for Bridge Capability

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Abstract:*Purpose: The objective of this study is to evaluate the load carrying capacity of a target bridge structure based on the simple slab bridge of concrete over 20 years of public service. Method: By performing static loading test and dynamic loading test, the displacement, strain, impact factor, and natural frequency values were measured and evaluated through analysis method. Result: The main results of this study are as follows. First, the maximum displacement and maximum strain of S1 were assessed at 2.917 mm and 44.720 $\mu\varepsilon$(tensile) and -13.760 $\mu\varepsilon$(compression), respectively, with S2 maximum displacement and maximum strain being 2.100 mm and 4.870 $\mu\varepsilon$(tensile), respectively. Second, the maximum measured impact factor was 0.191 in section S1 A-A, and the maximum measured impact factor was 0.155 in section S2 C-C. Third, the natural frequency was assessed at 6.086 Hz, and the measurement was found to be within the range of 6.152 Hz to 6.738 Hz. Conclusion: The tested bridge may be evaluated to show good behavior and characteristics for the design load.*

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I. Introduction

Load-carrying capacity evaluation is carried out on public bridge to assess the safety of passing loads, as damage and deterioration occur due to the influence of the surrounding environment, the enlargement and weighting of traffic vehicles, and the increase in traffic volume. The assessment of load carrying capacity is a very important factor in the safety and maintenance of bridges and includes appearance surveys, various tests, and structural analyses (Sung, 2017). The methods for calculating load carrying capacity is to take into account the load carrying rate during design live load, and to compensate for the load carrying rate by reflecting the actual data on damage, defects and material deterioration of the structure. The former method is adopted in the United State and Europe, and the latter method is adopted in South Korea and Japan (Mistry of Land, Infrastructure and Transport, 2019). As a result of the precision safety diagnosis conducted, most bridges without serious damage, defects or deterioration are secured against the design load. In addition, since bridges of First Class facilities (C-class) are in good maintenance condition with less than 3% of the total bridge, managers and inspectors of the facilities should carefully examine whether the load test is performed in assessing load carrying capacity (Hwang et al, 2011).

Loading test is performed to identify the static and dynamic behavior characteristics of the target structure and to evaluate load carrying capacity by measuring the actual behavior of the target structure according to the load of the test vehicle determined for the axial load. In general, loading test can be classified into Pseudo-Static loading tests and Dynamic test according to the loading method. Recently, due to the development of equipment, static loading test by loading test is replaced by longitudinal moving load, which continuously measures static loading of bridge. The Pseudo-Static loading tests identify the static behavior characteristics of the target bridge for the logistic loading test, the same as for static loading tests. It is also a test conducted to calculate the loading coefficient for load carrying capacity evaluation, such as static deformation rate and the ratio of stress response. On the other hand, dynamic driving tests are designed to measure and evaluate the dynamic behavior of basis structures, and differ in that they are conducted to identify the dynamic behavior characteristics of the bridge by measuring and analyzing Measured impact factor and Measured natural frequency of the bridge. Detailed guidelines for safety inspection and prevision safety diagnosis provide a guide for loading test (Bridge section, Detailed Guidelines below) (Ministry of Land, Infrastructure and Transport, 2010). However, most of these guides carry out loading test during precision safety diagnosis as there are many qualitative aspects. For instance, "If the load test is not suitable" refers that "The load carrying capacity assessed in a fair and theoretical manner exceeds the control level objective" and "When the Bridge is severely deteriorated or damaged and urgent reinforcement is required" (Jung, 2019). Therefore, it is absolutely necessary to establish quantitative and systematic standards.

Meanwhile, the safety and reliability of the public must be absolutely ensured during the common use period of the bridge and during the life extension period, so continuous management is required to maintain a load carrying capacity above the appropriate level. Effective bridge maintenance should prevent advance to the damage stage by detecting and taking preventive measure in advance, which could lead to defects, damage and degradation. If defects, damages and deterioration have already been carried out, economic maintenance will be carried out to extend the common life of bridge in order to prevent them from reaching large-scale repairs and reinforcement by taking appropriate measures and taking proper measures in the early stages. In the case of general bridges, it is known that if maintenance is not carried out, 25% of structural performance will be lost for 10 years after completion, 40% after 20 years, and 55% after 30 years. In particular in the case of low-grade bridges, it is known that appropriate maintenance would result in a reduction in load carrying capacity of approximately 17% 15 years after completion and 27% after 20 years after completion (Min and Kim, 2004). Therefore, it is necessary to conduct a load carrying capacity examination to assess the safety of vehicle passing loads in the event of bridge damage and deterioration.

Aim and objectives

This study highlighted a three-span concrete Slab bridge over 20 years of common life. The study aim to conduct a static load test and dynamic load test on the northern bridge of W bridge in South Korea, the bridge under test, in order to assess the load carrying capacity of the target structure by evaluating the behavior characteristics by non-destructive and loading test.

II. Methods

Item of loading test

In this study of load test items, static load tests were conducted to identify the characteristics of static behavior of the target bridge for external forces acting on the northern section of the W Bridge in Seoul, South Korea, and to calculate the various factors for load carrying capacity evaluation such as static displacement, strain and response ratio. The load test target of this bridge is P.S.C BEAM Bridge, which is a two-span continuous bridge, which was tested with a load test of LC1 to LC4 for one span and LC5 to LC8 for two spans, and with a load test of LC9, and LC10 at a location 1.35m away from A1 for measuring shear strain. Next, sensors according to the measured items were attached to the target component to identify the dynamic behavior characteristics for dynamic load testing, and test vehicle was driven by gradually increasing the maximum driving speed from 100km/hr to 10, 20, 30, 40, 60 and 80 km/hr. In this study, the same model vehicles of the same manufacturer were used to eliminate uncertainties in vehicle load applied to bridge structures. At this time, the dynamic behavior of the bridge was determined by measuring deflection, strain, and acceleration at the measurement point.

Selection of the targeted span for loading test

The upper structure of this bridge is P.S.C BEAM Bridge, and the total extension (L) designed as DB-18 load is 40.300m, with the maximum static moment action section selected as followed. In principle, the dynamic loading test was conducted in the direction of Ilsan, Korea for each speed (point of start → end of the vehicle).

Structure type	Test section
P.S.C BEAM	S_1
	S_2

Fig no 1. Span of the loading test

Measurement selection

For each item measured, the instrument selects the section with the maximum cross section force according to load weight and attaches it to the area where the maximum deflection and strain occurs. In order to identify the location of the maximum deflection and maximum deformation rate of the section subject to the loading test, a prior structural analysis was performed on the bridge subject to this test, and a measurement section was selected based on the results.

Sensor Attachment

Considering that the two-span continuous bridges in this study have the same span composition condition, a gauge was installed for one span during the loading test. A deflection meter was also installed on two intervals where external steel wires were installed. The gauge installation location was installed in consideration of the bridge's site conditions, such as symmetry, the behavior of the inner and outer girder, and the connection of the abdominal structure.

III. Results

Results of Static loading test

The results of displacement and strain measurement of the static load test of the bridge subject to this test are specified in the following tables. Displacement is a very important characteristics because it is relevant to the overall rigidity of the members that make up the bridge, so if the deflection of a particular member is high under the same load conditions, it can be expected to damage the member or infer design or construction errors. First, each measurement gauge displacement measured at the location of LC1 to LC4, one span of section A-A, was shown in the range of -0.358 to 2.917mm, as shown in Table no 1, with a value of 2.917mm, the maximum displacement at LC2.In order to identify the lateral effects of S1 and S2 based on static loading test results, strain and displacement attached to each section under load conditions are as follows. Considering the structural characteristics of the bridge and the error caused by the difference in sensors, the values of LC1 and LC4 are generally measured with similar symmetry, so the behavior through lateral distribution analysis is considered to be relatively satisfactory. Next, the strain (ε) for each measuring gauge measured at the location of LC2 to LC4, which is one span under the same conditions, was distributed in the range from -14.769 to 44.720 * 10^{-6} as shown in Table no 2 and showed a value of 2.917 mm, the maximum displacement at LC2.

Table no 1: Shows displacement in the static loading test (S1, section A-A)

Gage No		Static				Remark
		L.C1	L.C2	L.C3	L.C4	
1 Clear span	DT1	2.206	-0.051	-0.002	0.003	mm
	DT2	2.319	0.523	0.061	0.004	mm
	DT3	0.279	2.917	0.239	-0.01	mm
	DT4	0.024	0.658	2.631	0.377	mm
	DT5	0.001	0.074	1.004	2.114	mm
	DT6	-0.003	-0.003	0.065	1.141	mm
2 Clear span	DT7	-0.274	-0.027	-0.018	-0.003	mm
	DT8	-0.145	-0.299	-0.103	-0.010	mm
	DT9	-0.026	-0.181	-0.358	-0.126	mm
	DT10	-0.003	-0.002	-0.061	-0.160	mm

Table no 2: Shows strain in the static loading test (S1, section A-A)

Gage No	Static				Remark
	L.C1	L.C2	L.C3	L.C4	
ST1	4.831	0.488	0.844	0.518	με
ST2	14.291	4.150	1.382	0.201	με
ST3	3.190	23.188	3.366	-0.132	με
ST4	1.239	10.870	39.162	5.062	με
ST5	-0.199	1.636	22.66	44.720	με
ST6	0.135	1.463	1.325	16.153	με
ST7	-14.769	-0.148	1.256	0.688	με
ST8	-6.434	-8.424	-4.660	-0.410	με
ST9	-0.782	-7.879	-11.663	-3.364	με
ST10	1.715	2.374	-1.434	-5.443	με

Next, each measurement gauge displacement measured at the location of LC5 to LC8, which is two spans of section B-B, was shown in the range of -0.286 to 2.100mm, as shown in Table no 3, and the maximum displacement at LC6. In addition, the strain rate (ε) for each measuring gauge measured at the location of LC 1 to LC 4 in the same condition was 0.014 to $0.870*10^{-6}$ as shown in Table no 4, and the strain rate (ε) for each measuring gauge measured at the location of LC5 to LC8 in the two spaces was measured in the range of 0.092 to $4.870*10^{-6}$ (Table no 4).

Table no 3: Shows displacement in the static loading test (S2, section B-B)

Gage No	Static				Remark
	L.C5	L.C6	L.C7	L.C8	
DT1	-0.260	-0.011	0.012	-0.011	mm
DT3	-0.097	-0.250	-0.093	-0.001	mm
DT4	-0.017	-0.141	-0.286	-0.142	mm
DT6	-0.003	-0.005	-0.032	-0.112	mm
DT7	1.989	0.003	-0.002	0.026	mm
DT8	0.377	2.100	0.302	0.006	mm
DT9	0.012	0.578	1.891	0.317	mm
DT10	0.004	-0.035	0.050	1.572	mm

Table no 4: Shows strain in the static loading test (S2, section C-C)

Gage No	Static								Remark
	L.C1	L.C2	L.C3	L.C4	L.C5	L.C6	L.C7	L.C8	
ST11	0.870	0.238	0.028	0.383	0.708	0.168	0.092	0.277	με
ST12	0.732	0.445	0.014	0.256	0.493	3.084	3.266	1.325	με
ST13	0.791	0.343	0.515	0.565	0.242	2.056	4.870	2.008	με
ST14	0.608	0.137	0.427	0.622	0.320	0.279	2.916	4.016	με

Based on the static loading test results, the maximum displacement and maximum strain of the upper and lower flanges of S1 were assessed at 2.917mm, 44.720 με (tensile), and -13.760 με (compression), respectively, with S2 maximum displacement and maximum strain of 2.100 mm and 4.870 με (tensile), respectively. Further, it was analyzed that the displacement value of the continuous bridge was generated as a result of analyzing the displacement value of the other span when loading for each span. Meanwhile, the displacement response curve, which shows the strain over time for each major case of the load test previously presented, is shown as follows.

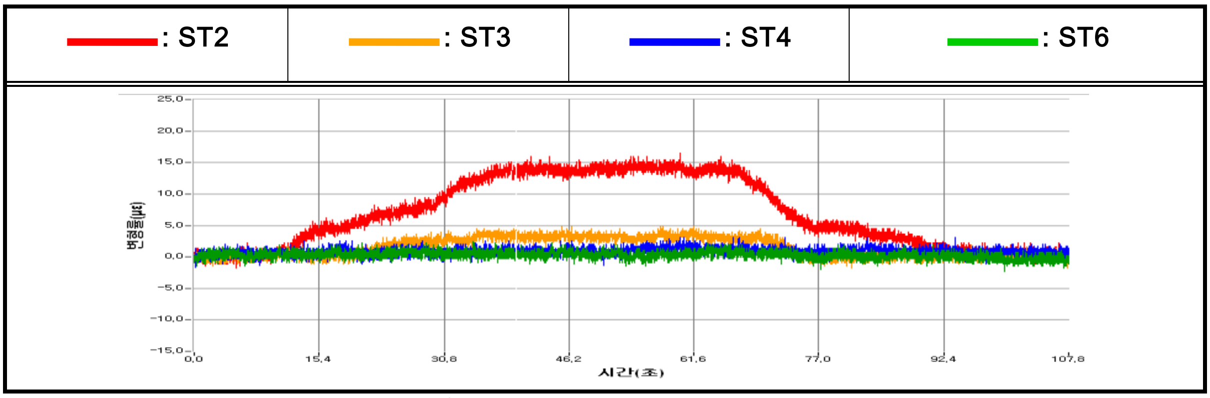


Fig no 3-a. Variation of strain with time (section A-A : ST2, ST3, ST4, ST6) - LC1

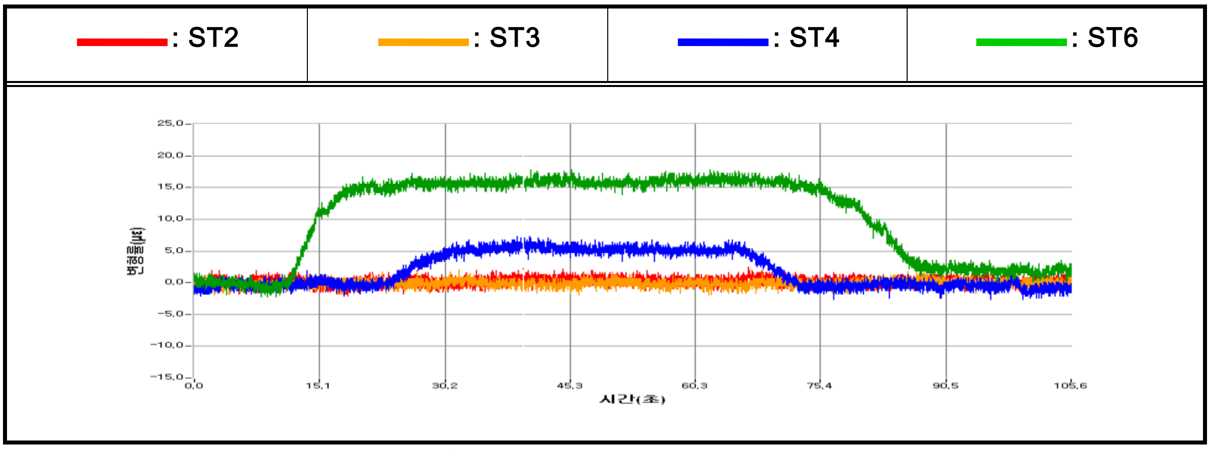


Fig no 3-b. Variation of strain with time (section A-A : ST2, ST3, ST4, ST6) - LC4

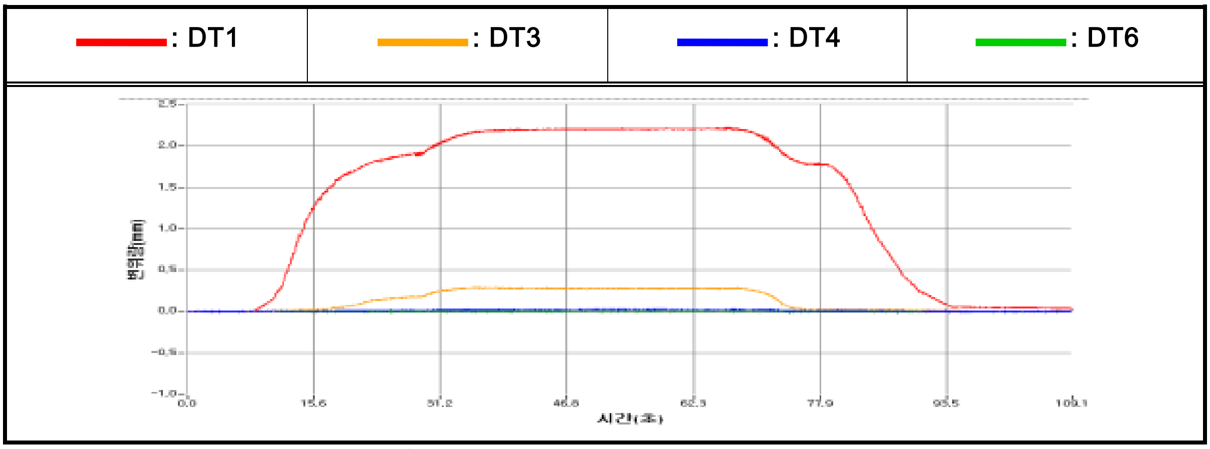


Fig no 3-c. Variation of displacement with time (section A-A : DT1, DT3, DT4, DT6) - LC1

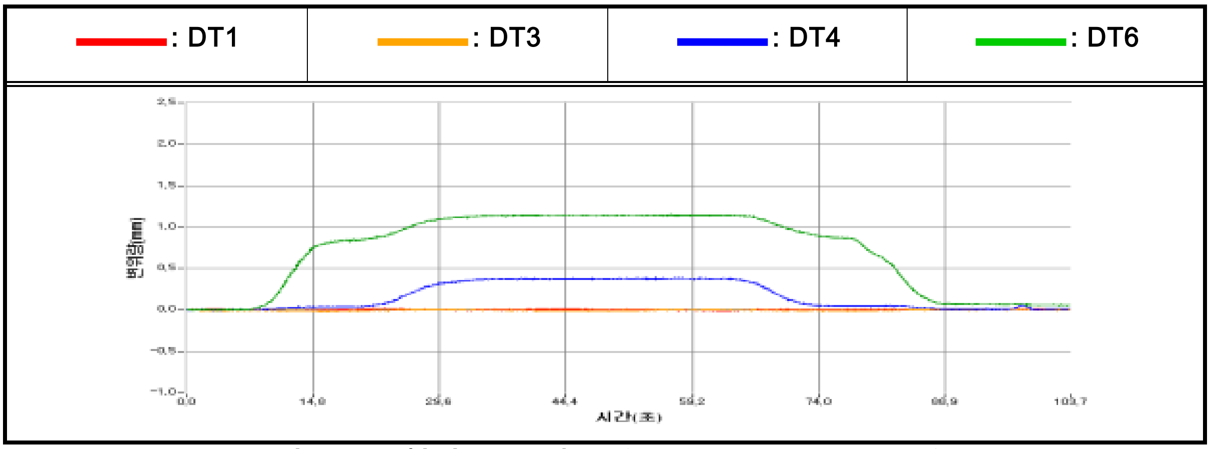


Fig no 3-d. Variation of displacement with time (section A-A : DT1, DT3, DT4, DT6) - LC4

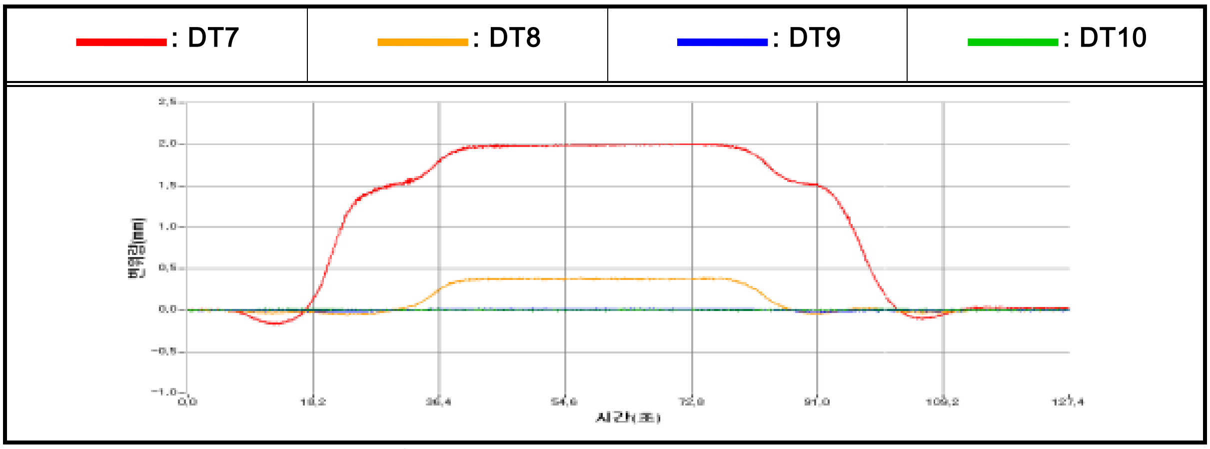


Fig no 3-e. Variation of displacement with time (section C-C : DT7, DT8, DT9, DT10) - LC5

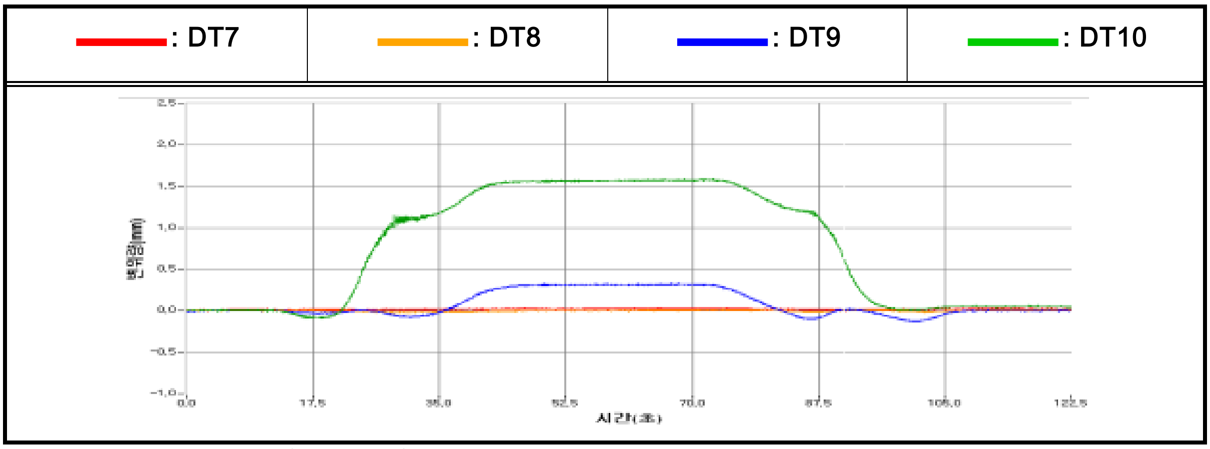


Fig no 3-f. Variation of displacement with time (section C-C : DT7, DT8, DT9, DT10) - LC8

Result of Dynamic load test

In this study, the impact of coefficient for the bridge under test was measured through dynamic loading test, and the result was presented to Table no 5. When driving above a certain speed of the vehicle, displacement and strain of the member will occur above the static load. This is due mainly to factors such as bumps on the bridge deck, deceleration and acceleration of the vehicle, or the interaction of the vehicle before and after. A numerical representation of this is the degree of impact as a coefficient of impact. For measurements with small response values, the actual impact coefficient was excluded from the calculation of the actual impact coefficient and the impact coefficient was selected using the gauge installed on the driving lane where the measurement value was generated significantly. In this study, the test vehicle was driven with the second lane of the bridge as the driving lane with the driving path constant. The vehicle speed phase was measured at a speed between 10km/h and 80km/h, increasing by 10km/h, and the results of the test are presented in Table no 5 and Figure no 4.

As shown in Table no 5, for DT1 in the upper and lower girder flange of S1's static moment, the impact coefficient was between 0.045 and 0.242, with DT2 being between 0.019 and 0.191 and DT3 begin between 0.016 and 0.212. As a result of the impact coefficient measurement, the maximum actual impact coefficient is 0.242 in S1 A-A, which is less than the theoretical impact coefficient of 0.252, indicating that the live load impact is not significant and safety is sufficiently secured. In S2 C-C selections, DT7 was distributed between 0.059 and 0.198 and DTB between 0.036 and 0.155. As a result of the impact coefficient measurement, the maximum actual impact coefficient was 0.198 in S2 C-C section, which is less than the theoretical impact coefficient of 0.252, confirming that the live load impact is not significant and safety is sufficiently secured. On the other hand, it is shown that the higher the speed of the test vehicle, the higher the overall impact coefficient, and the change in the impact coefficient according to the speed of the test vehicle for DT2, DT3 and DT8.

Table no 5: Shows impact factor with vehicle's velocity

		section A-A S1			section C-C S2	
		DT1	DT2	DT3	DT7	DT8
10km/hr	Ddyn	0.162	1.437	0.786	0.162	0.659
	Dsta	0.150	1.384	0.756	0.153	0.634
	Impact factor(i)	0.080	0.038	0.040	0.059	0.039
20km/hr	Ddyn	0.162	1.394	0.619	0.164	0.611
	Dsta	0.155	1.348	0.609	0.141	0.560
	Impact factor(i)	0.045	0.034	0.016	0.163	0.091
30km/hr	Ddyn	0.187	1.423	0.677	0.166	0.626
	Dsta	0.174	1.397	0.633	0.139	0.604
	Impact factor(i)	0.075	0.019	0.070	0.194	0.036
40km/hr	Ddyn	0.197	1.489	0.716	0.192	0.620
	Dsta	0.162	1.321	0.645	0.155	0.566
	Impact factor(i)	0.216	0.127	0.110	0.239	0.095
60km/hr	Ddyn	0.230	1.900	0.897	0.192	0.609
	Dsta	0.187	1.615	0.747	0.168	0.560
	Impact factor(i)	0.230	0.176	0.201	0.143	0.087
80km/hr	Ddyn	0.205	1.660	0.743	0.200	0.665
	Dsta	0.165	1.394	0.613	0.167	0.576
	Impact factor(i)	0.242	0.191	0.212	0.198	0.155
Maximum impact factor		0.242			0.198	
Design impact factor		0.252				

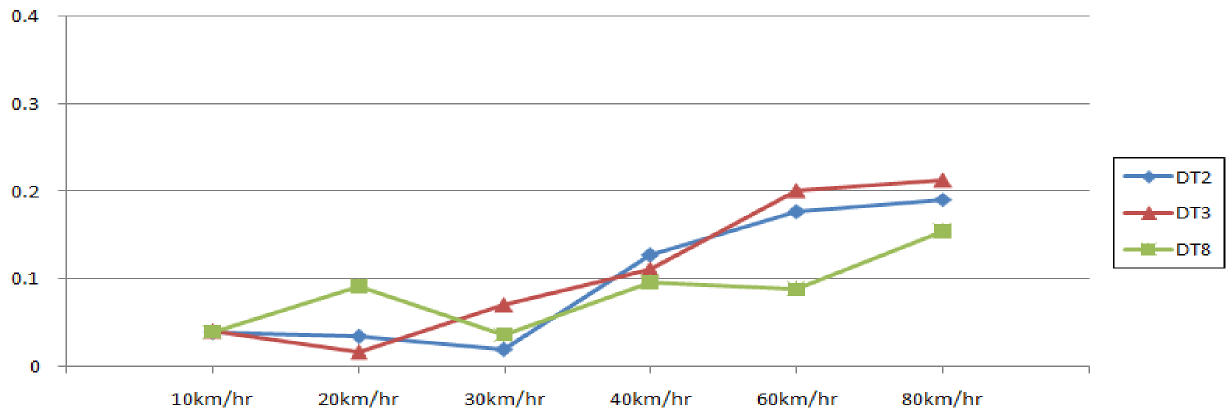


Fig no 4. Variation of impact factor with vehicle's velocity

Meanwhile, an accelerometer was attached to the S1 of middle of static zone to evaluate the inherent frequency of this bridge and dynamic response was obtained for each driving speed. It was also analyzed using the displacement gauge attached to the driving lane. In the case of structural analysis, modelling was performed using the MIDAS/Civil 2012 analysis program, which is a general-purpose structural analysis program, and the eigenvalue analysis technique was applied by comparing with the actual measured frequency data measured in this study. The analysis results were compared with the experimental results, and for the analysis results, 6.086 Hz was analyzed in the third mode, which was significantly generated in the Z direction, from the results of the analysis by attaching the site acceleration gauge in the model year direction and the mass participation rate by mode (Figure no 5). According to the results of the experiment, the natural frequency of the bridge was analyzed at 6.152Hz to 6.738 Hz, and the stiffness of the bridge was judged to be satisfactory. On the other hand, the FFT analysis was performed on the section where the vehicle was freely vibrating outside the target range to calculate the natural frequency (Figure no6). The difference in the value of the natural frequency is believed to have been caused by the difference between the rigid value of the bridge considered at the time of construction and the rigid value of the bridge in the state of construction.

Table no 6: Showsfrequency measurement as vehicle's velocity

Velocity		10 km/hr	20 km/hr	30 km/hr	40 km/hr	60 km/hr	80 km/hr
Natural frequency (Hz)	ACC	6.152	6.348	6.641	6.738	6.250	6.250
	Gage	7.715	7.617	7.520	6.934	7.129	7.422
Range		- Natural frequency(acceleration) : 6.152 Hz ~ 6.738 Hz - Theoretical frequency: 6.086Hz					

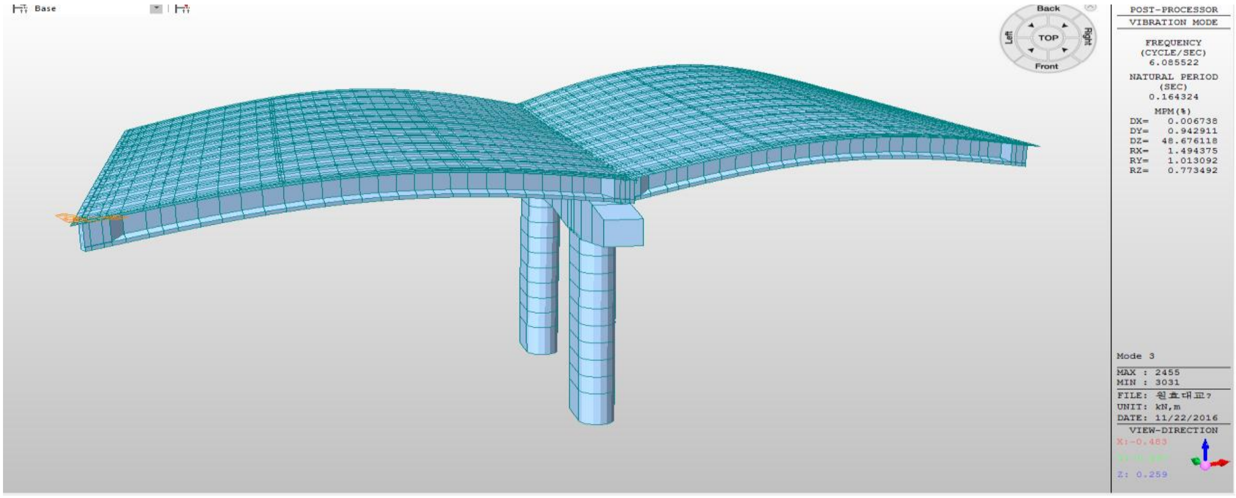
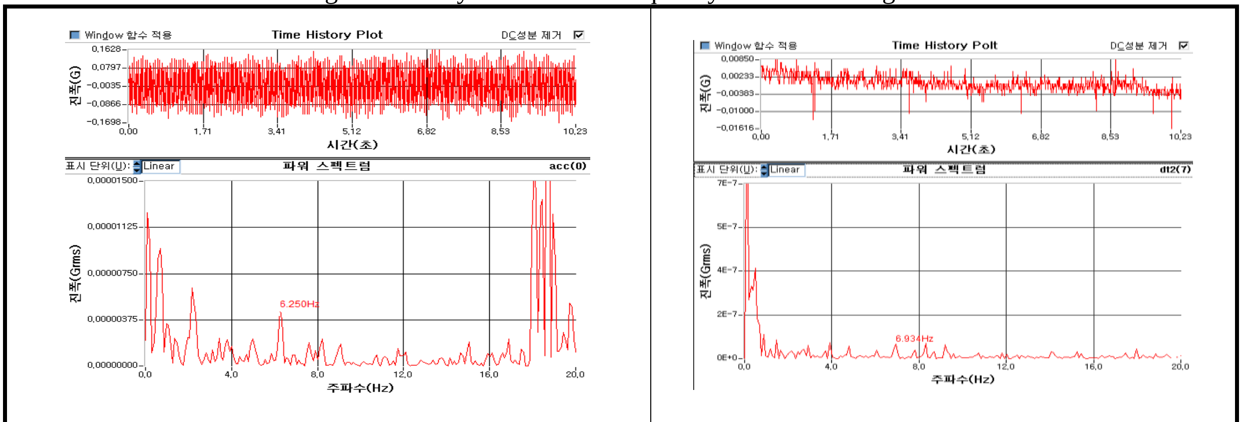


Fig no 5. Analysis of natural frequency of the test bridge



60km/hr(ACC)	40km/hr(DT2)

Fig no 6. FFT Analysis result for acceleration response curve

IV. Conclusion

In this study, the load carrying capacity of the target structure was evaluated for concrete simple slab bridges with 20 years of common life. There are currently some bridges with 20 years of public life in South Korea, and in the case of these bridges, only about 70% of the initial load carrying capacity can be predicted. Accordingly, the load carrying capacity assessment for safety assessment of vehicle passing load is necessary as deterioration or damage of aging domestic bridges occurs. In addition, this study is different compared to prior studies in that it has identified the dynamic behavior characteristics of the bridge by measuring and analyzing the actual impact factor and the actual frequency of the target bridge, highlighting the northern bridge of W Bridge in Seoul, which is a representative domestic bridge that has aged as a simple slab bridge in South Korea.

The main results of this study are summarized as follows. First, the maximum displacement and maximum strain of S2 were assessed at 2.917mm, 44.720 με(tensile), -13.760 με (compression) and the maximum displacement and maximum strain of S2 were 2.100mm and 4.870 με (tensile) respectively. Second, the maximum actual impact coefficient was 0.242 in Section S1 A-A. The maximum actual impact coefficient is 0.198 in section S2 C-C, which is less than the theoretical impact coefficient of 0.252, so the effects of live load impact are not significant, and safety is sufficiently secured. Third, as a result of analyzing and measuring the natural frequency of this bridge, it was analyzed that the site acceleration gauge was 6.086 Hz in third mode with a large Z-direction, and the strength of the bridge was judged to be good as the natural frequency was measured at 6.152 Hz to 6.738 Hz. Based on the above results, the bridge subject to test can be evaluated as showing reasonable behavior and characteristics for the design load.

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