P.C. BOX 교량의 재하시험 및 원격계측 유지관리 시스템

Load Test and Remote Monitoring of P.C. Box Girder Bridge

*이 성 우[1]　　배 두 병[2]　　이 선 구[3]

*Sung Woo Lee[1], Doobyong Bae[2] and Sun Goo Lee[3]

ABSTRACT

Load test for newly introduced precast segmental bridge is carried out to experimentally evaluate load carrying capacity. Analysis accompanied with the test is also performed and the results are used in the evaluation. In addition to initial evaluation of the bridge by load test, remote dynamic monitoring system to perform realtime assessment of the bridge condition is also under development. In this paper the procedure and results of load test and evaluation are presented along with introduction of dynamic monitoring system.

INTRODUCTION

Construction of precast prestressed segmental bridge is ever increasing in recent days in Korea due to economic and aesthetic reasons. Viaduct of Gangbyun 1-1 Riverside Highway, the first segmental bridge of external prestressing type in this country, is completed and opened to the traffic just recently. The bridge is part of the Inner Circular Highway of Metropolitan Seoul and located along the Han River.

To evaluate initial load carrying capacity and overall performance of this newly introduced bridge of this kind, load tests are conducted prior to commissioning the viaduct(Lee and Bae 1995). Evaluation is carried out both in experimental method using the results of static and dynamic load tests and in independent analytical method(Aalami, 1995) taking into account time-dependent effects characteristic of segmental construction.

In addition to initial evaluation by load test, a program to assess bridge condition by dynamic monitoring is under development. It is designed to monitor continuously the performance and any defects of the bridge, thereby ensure safety of this newly introduced bridge. To monitor dynamic characteristics, on-line telemetry system is prepared to perform signal processing at remote data control center. Methodology of handling and analysis of bulk

1) 국민대학교 토목공학과 부교수
2) 국민대학교 토목공학과 조교수
3) (주) 동명기술공단 구조부 이사

of measured data and setup for early warning system is still under development. In this paper some essential part of load test and dynamic monitoring system is presented.

DESCRIPTION OF BRIDGE

Gangbyun 1-1 Riverside bridge is a viaduct consisting of a number of seven span frames. The seven span sections occur between the expansion joints of the super structure. The frame considered in this study is a typical 7-span continuous segmentally constructed precast single cell box girder bridge with externally post-tensioned tendons. Each span is 50m and consists of 17 segments. Span-by-span method of construction is used. Segments of each span are integrated together and to that of the remainder of the spans by means of 16 draped tendons placed externally within the void of the box girder by way of deviation blocks. The tendons each stretch over one span and are stressed and anchored at the diaphragm over each support. The support conditions of each span section are identical, with all supports being movable supports except for the third pier of each section which is hinged. The layout of external unbounded tendons in a typical span is shown in Fig. 1.

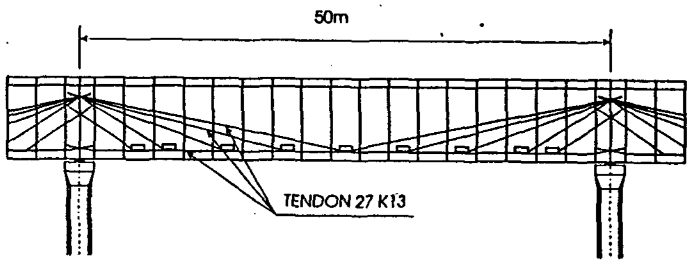


Fig. 1. Typical profile of externally prestressed segmental bridge

LOAD TEST AND EVALUATION

Experimental evaluation procedure

Evaluation of load carrying capacity based on allowable stress design and experiment is carried out according to guideline for evaluation of concrete bridge construction(Ministry of Construction 1994). Basic load carrying capacity P for Korean standard truck loading DB24 is defined as follows:

$$P = 24(\sigma_a - \sigma_d) / \sigma_{24} \quad (1)$$

Where, σ_a = allowable stress; σ_d = dead load stress; and σ_{24} = stress for DB 24 including impact factor. Operating load carrying capacity P' is then determined by multiplying correction factors to basic capacity P as follows:

$$P' = P \times K_s \times K_r \times K_t \times K_o \quad (2)$$

Where, K_s = stress correction factor; K_r = correction factor for deck condition; K_t = correction factor for traffic; and K_o correction factor for other conditions. In Eq. (2) K_s factor is defined as follows:

$$K_s = \sigma_{TA}(1 + i_{TA}) / \sigma_{TM}(1 + i_{TM}) \quad (3)$$

Where, σ_{TA} = computed stress for test truck; i_{TA} = code specified impact factor; σ_{TM} = measured stress for test truck; and i_{TM} = measured impact factor. Since bridge is newly constructed, all correction factors except K_s are considered to be 1.0 in the evaluation.

Load test

Testing equipment and sensors Load tests are carried out in two stages, i.e., static and dynamic. During the static tests, stresses and displacements are measured with strain gauges and displacement transducers. These sensors are placed on the bridge where maximum values are expected. Measured stress data are used to determine stress correction factor K_s (Eq. (3)). Displacement data are used in checking serviceability by comparing code specified permissible live load deflection.

In dynamic tests, various responses are measured with strain gauges, accelerometers, and various displacement transducers (LVDT, laser beam).. Typically stress and displacement responses are used to obtain experimental impact factor(i_{TM}) which is again used to determine K_s factor. Acceleration data are used to obtain dynamic properties.

The instruments are distributed throughout the span and connected to data acquisition system. Photo 1 and 2 show data acquisition system for static and dynamic test respectively.

Fig. 2 shows layout of measurement locations used in this study. Though not shown in the Fig., some more measurements are carried out during test. After load test, sensors in this locations are used in the dynamic monitoring for ambient traffic.

Static test Static tests are carried out using four test trucks. Fig 3. shows axile force of the typical test truck. Photo 3 shows typical arrangement of test truck during the static test.

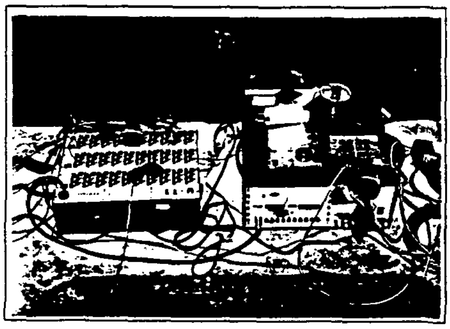


Photo 1. Data acquisition for static test

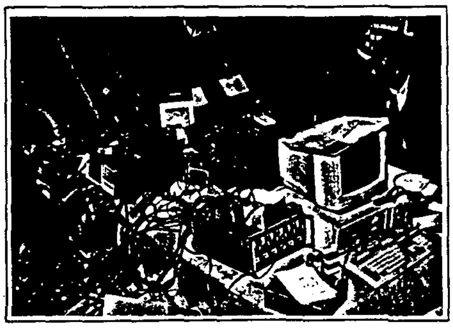


Photo 2. Data aquisition dynamic for test

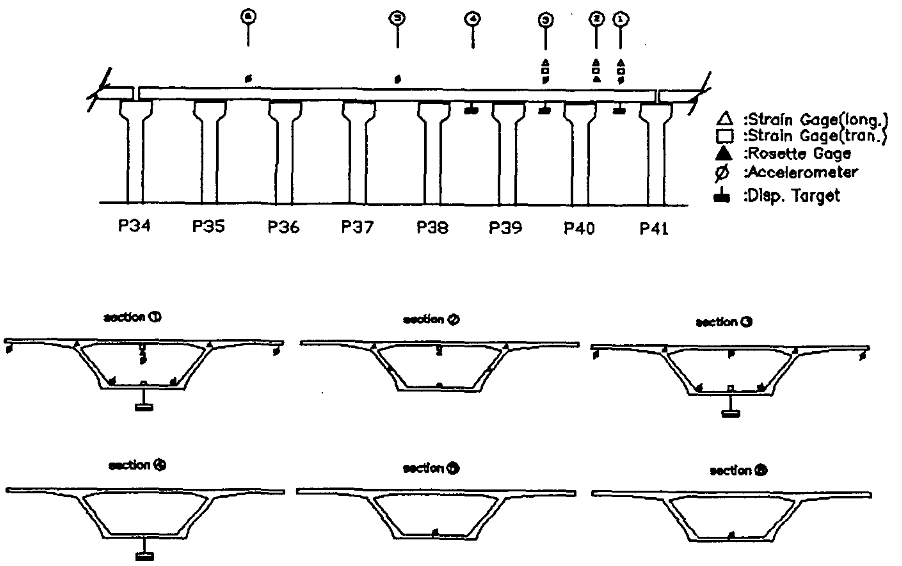


Fig. 2. Layout of measurement locations

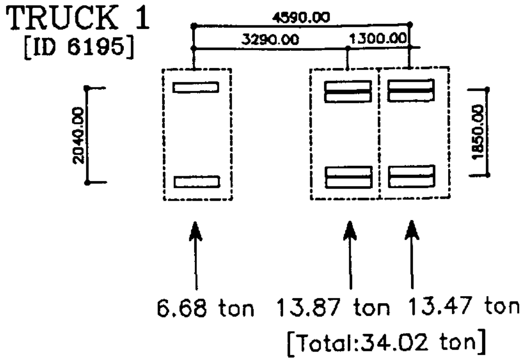


Fig. 3. Axile force of test truck

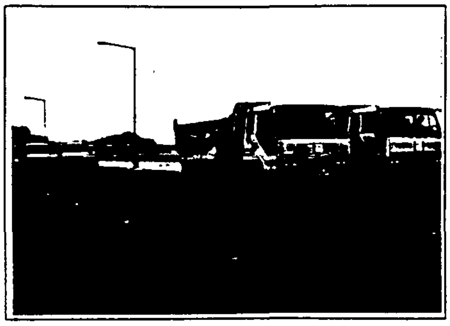


Photo 3. Typical arrangement of the test truck

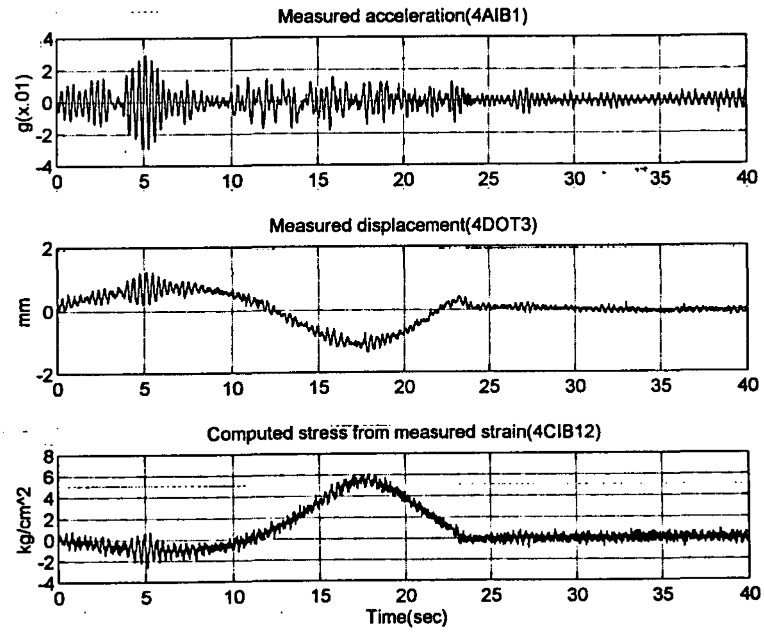


Fig. 4. Example of measured data at center of end span on bottom slab(run case 5, 15km/hr)

Variety of load cases are treated during the static tests. In each load case, combination of trucks are located at center of each span, center of two adjacent spans, center of one other spans, top of expansion piers and quarter point of end span. In the above load cases, patterns of truck loading are as follows: (1) Single truck in each lane; (2) two trucks side-by-side with 2-lane combination; (3) three trucks side-by-side with 3-lane combination; and (4) four trucks side-by-side with 4 lanes fully occupied. The results of static test along with comparison with analysis results are described in other section.

Dynamic test Dynamic tests are conducted using two test trucks. During the tests, runs are made using the following patterns: (1) Single truck; (2) two trucks side-by-side; (3)two trucks in line; and (4) single truck through wedge block. Fig.4 shows one of the time history plots of data measured for a run during tests from different measurement devices.

One of the main objective of the dynamic tests is the experimental evaluation of the impact factor and it is defined as follows(Ministry of construction 1994):

$$i_{TM} = (1 - DAF) / \sqrt{N} \quad (4)$$

Where N is number of loaded trucks and DAF is dynamic amplification factor defined as follows:

$$DAF = R_{dyn}/R_{sta} \tag{5}$$

Where, R_{dyn} = maximum dynamic response; and R_{sta} = maximum response from quasi-static test i.e., crawl run.

Fig. 5 shows displacement response of LVDT for each speed. Using these responses DAF can be evaluated. Table 1 and Fig. 6 shows impact factor computed from measured data of several strain gauges and displacement transducers. As shown in the Fig. 6, maximum value of impact factor occurs at different velocity for each measurement locations. In the evaluation average value of impact factor is used.

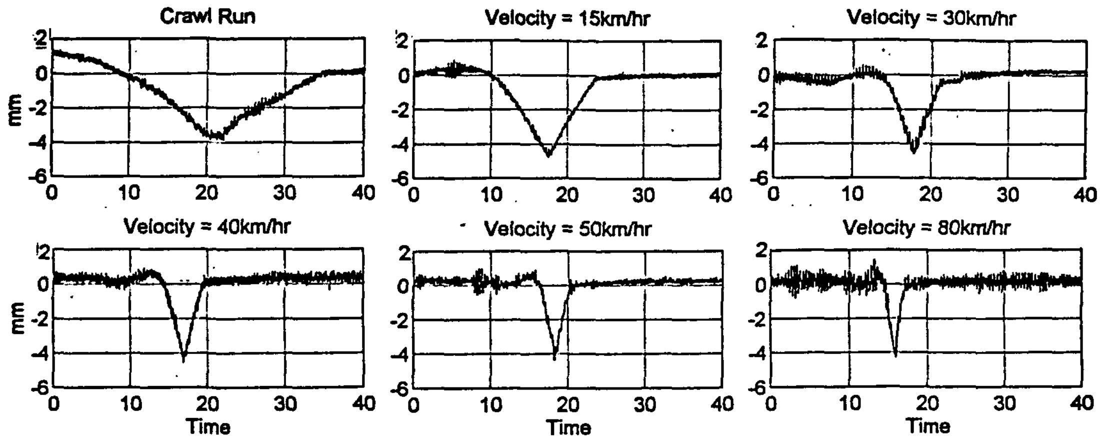


Fig. 5. Displacement response at center of end span on tip of the overhang(gage ID: 4DOT2)

Table 1. Experimental impact factor at center of end span

GAGE ID	Loaded lane	Velocity (Km/hr)						Ave.	Meas. dir.
		5-10	15	30	40	50	80		
Strain gage: 4CIT2	1	·	·	·	·	·	·	·	Trans
(Mid. of top slab)	2	0.0	0.170	0.090	0.330	0.330	0.340	0.250	Trans
Strain gage: 4COT5	1	0.0	0.140	0.000	0.080	0.070	0.010	0.060	Trans
(Tip of overhang)	2	·	·	·	·	·	·	·	Trans
LVDT: 4DOT2	1	0.0	0.230	0.187	0.175	0.129	0.108	0.166	Long
(Tip of overhang)	2	0.0	-0.090	-0.020	0.180	0.210	0.210	·	Long
Strain gage: 4DOT3	1	0.0	-0.135	0.015	-0.019	0.018	-0.014	·	Long
(Mid. of bot. slab)	2	0.0	0.110	0.030	0.016	0.080	0.010	0.078	Long
Strain gage: 4CIT1	1	·	·	·	·	·	·	·	Long
(Mid. of top slab)	2	0.0	0.220	0.190	0.460	0.270	0.340	0.296	Long
Strain gage: 4CIB9	1	0.0	0.026	0.034	0.021	-0.008	-0.045	·	Long
(Corner of bot. slab)	2	0.0	-0.003	0.026	0.030	-0.003	0.033	0.030	Long
Strain gage: 4COB12	1	0.0	0.020	-0.060	0.052	-0.038	-0.079	·	Long
(Mid. of bot. slab)	2	0.0	0.037	0.034	0.110	0.120	0.110	0.082	Long
Average								0.130	Long

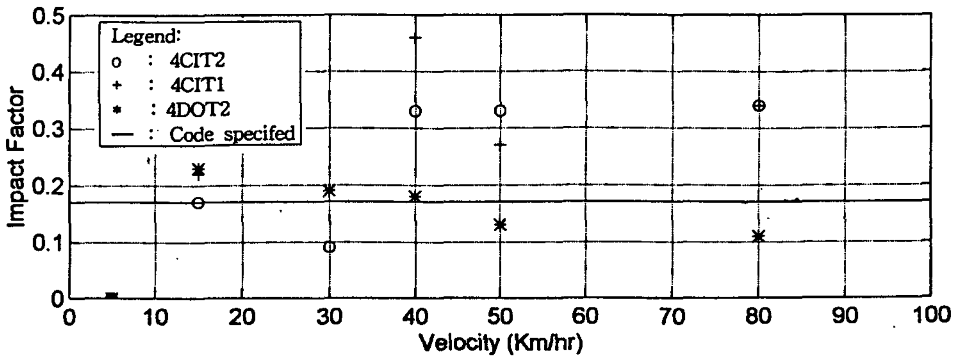


Fig. 6. Experimental impact factor

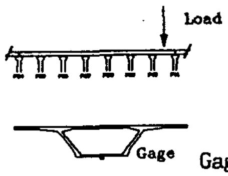
Analysis

To evaluate the bridge analytically, 2D analysis considering time-dependent effects of segmental construction is carried out. Then evaluation independent to original design is performed using the results.

To do experimental evaluation, 3D finite element analysis is also carried out. The results of analysis are used to obtain σ_{24} in Eq.(1) and σ_{TA} in Eq.(3).

Table 2 shows typical comparison of results of static test and analysis. As shown in this table some of the results are agree well each other but some others are not. For this reason correction of stress values is required in the evaluation. These results are incorporated in correction factor calculation in Eq. (3).

Table 2. Comparison of stress results

Location	Loaded lane	Measured (kg/cm^2)	Analysis (kg/cm^2)		Measured/Analysis	
			2D	3D	2D	3D
 Gage ID: 4D0B13	L1	7.03	7.26	7.82	0.97	0.90
	L2	4.07	7.26	6.83	0.56	0.60
	L1,2	12.22	14.52	14.65	0.84	0.83
	L2,3	8.88	14.52	13.66	0.61	0.65
	L1,2,3	16.29	21.78	21.48	0.75	0.76
	L1,2,3,4	24.43	29.04	29.30	0.84	0.83

Evaluation of bridge

Serviceability evaluation   Serviceability of the bridge is evaluated comparing measured live load deflection($\delta_{24,M}$) with code permissible one. Measured deflection equivalent to DB24 design truck loading($\delta_{24,M}$) is computed as follows:

$$\delta_{24,M} = \delta_{24,A} \times \frac{\delta_{TM}(1+i_{TM})}{\delta_{TA}(1+i_{TA})} \tag{6}$$

Where $\delta_{24,A}$ = computed maximum deflection for design truck loaded in full 4 lanes; δ_{TM} = measured deflection from test trucks loaded in full 4 lanes; and δ_{TA} = computed deflection from test trucks loaded in full 4 lanes. Serviceability is checked at center of end span in which maximum displacement is expected. As shown in the table it satisfies deflection serviceability criteria of the code with far enough margin. Table 3 shows the results of the serviceability evaluation.

Table 3. Serviceability evaluation at center of end span

(unit : mm)

Location	δ_{TM}	δ_{2AM}	Permissible LL deflection(L/800)	Remark
Bottom side	6.84	9.58	62.50	OK
Overhang	7.33	9.05	62.50	OK

Experimental strength evaluation Experimental strength evaluation is carried out as per evaluation procedure in eq. (1) and eq. (2). Table 4 shows the results of flexural strength evaluation of the bridge in the longitudinal direction. Though not shown in the paper, evaluation in traverse direction is also carried out. As shown in the table flexural load carrying capacity of the bridge is more than four times DB24 design load. Thus it is considered that the bridge possesses enough safety margins in flexure.

Analytical evaluation From the results of 2D analysis considering time-dependent effect of segmental construction, analytical evaluation is carried out. Table 5 shows the capacity demand ratio in longitudinal and transverse directions. As in the experimental evaluation analytical evaluation also shows that the bridge has resonable safety margins(Aalami, 1995).

DYNAMIC MONITORING

In addition to initial evaluation of bridge by load test, dynamic monitoring system is designed to assess bridge condition. By continuously monitoring the dynamic characteristics for the ambient traffic avoiding the interruption of traffic, it is believed to be possible to detect

Table 4. Experimental evaluation of compression side in longitudinal direction at end span

	Center of span (Box top)		Interior support (Box bottom)	
Allow. stress (σ_a, kg/cm^2)	-180.00		-180.00	
DL stress (σ_d, kg/cm^2)	-63.70		-64.40	
LL stress(σ_{24}, kg/cm^2)	2D	-13.51	2D	-26.66
	3D	-28.87	3D	-30.19
Basic capacity(P)	2D	206.60	2D	104.10
	3D	96.60	3D	91.90
K_s (Stress correction factor)	2D	1.00	2D	1.16
	3D	3.02	3D	1.24
Operation capacity (P' = P x K_s)	2D	206.60	2D	120.76
	3D	291.73	3D	113.96
P'/DB24	2D	8.61	2D	5.03
	3D	12.16	3D	4.75

Table 5. Analytical evaluation based on time-dependent 2D analysis

Description	Location	Longitudinal		Transverse		Remark
		Capacity/demand	Ratio	Capacity/demand	Ratio	
Flexural	Center of end span	10339/2840	3.64	128/116	1.10	Moment ratio(t-m)
	Support face of end span	5680/3120	1.82			
Shear	1st support	490/482	1.02	71.5/46.7	1.53	Shear ratio(ton)
	2nd support	490/283	1.73			

defects such as: (1) Prestressing loss, directly related to frequency; (2) cracking, which reduces natural frequency and increases damping; and (3) movement of the supports, affecting dynamic behavior, mainly of frequency and damping. Since the system is still under development, introduction of the system will be given in this paper.

Procedure of dynamic monitoring
For the sensors such as strain gauges, accelerometers and LVDTs shown in Fig. 2, remote data acquisition system is designed utilizing telemetry system. Fig. 7 shows schematics of remote monitoring system.

As shown in the Fig. 7, all the real-time response data are transferred to remote control center via modem. Then these data are analyzed and evaluated to do proper action such as call for detailed inspection or shut down traffic to prevent further damage etc. Early warning system will be designed based on these informations.

All procedures are controlled through program called BRMS(Bridge Remote Monitoring System) in the data control center. Fig. 8 shows some of the screen displays of BRMS for data control and acquisition.

Some techniques for evaluation of measured data Evaluation of measured data is one of the important sequence in dynamic monitoring. Although displacement and strain measurement are usually preferred for the evaluation of dynamic properties, acceleration data can be integrated to obtain reliable estimate of displacement. With this integrated displacement response, impact factor and mode shapes can be obtained. Accelerometers can be mounted very easily while installation of displacement transducers require expansive scaffolding. For this reason, integrated displacement method is very cost-effective and fast way of obtaining dynamic characteristics. This idea is introduced in some literature(Pautre 1995). Following the procedure in reference 6 (S.G. Lee and S.W. Lee 1995) displacement response from integrated acceleration data can be easily obtained. Fig. 9 shows example of integrated displacement from measured acceleration of tested bridge together with measured displacement applying this technique. As shown in the Fig. 9 they agree pretty well each other.

For evaluation of dynamic characteristics in real time, on-line FFT spectrum analysis is also considered to be necessary. This technique is developed in recent days by authors. Fig. 10 shows such FFT spectrum for measured acceleration data in Fig. 9. As shown in the Fig. 10, the shapes of spectrum are different when traffic is passing the measurement location.

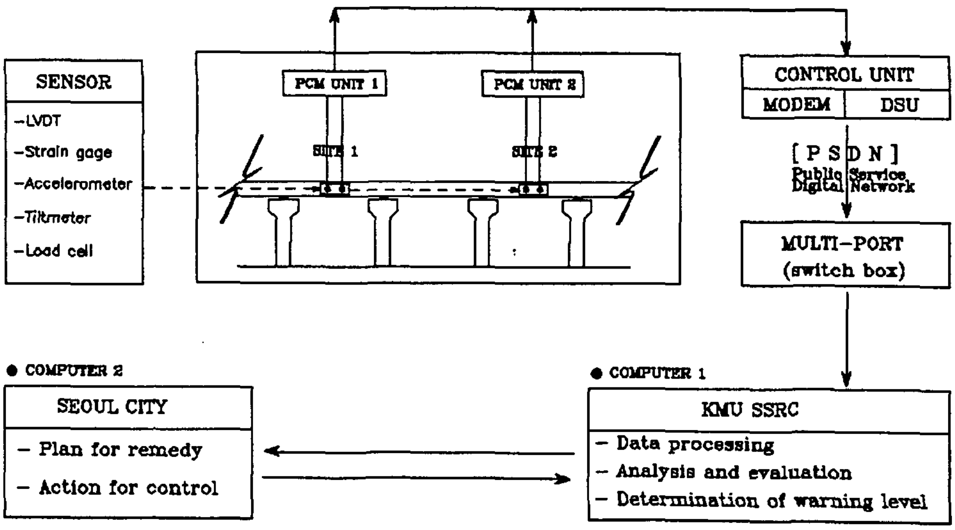
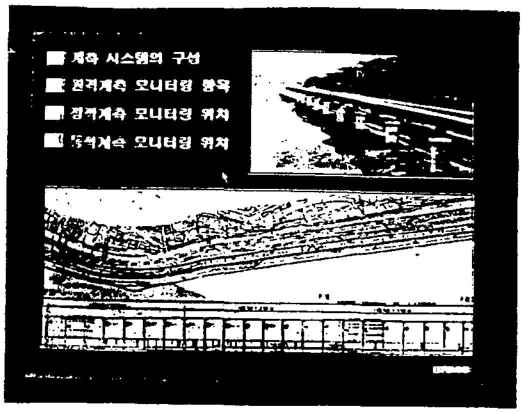
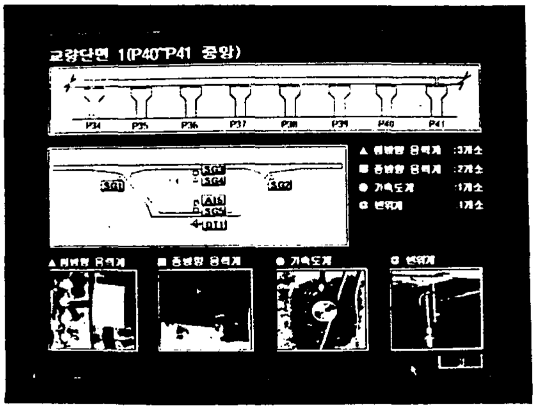


Fig. 7 Schematics of remote monitoring system

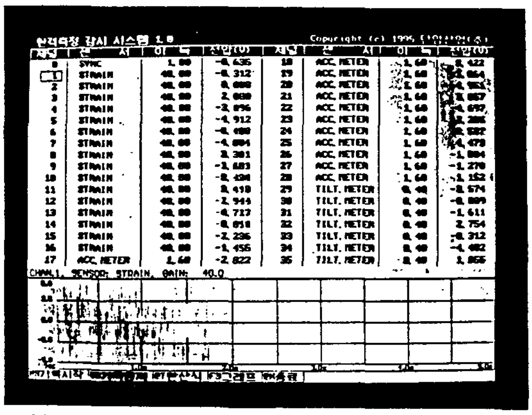
(a) Location map



(b) Viaduct layout



(c) Measurement layout



(d) Realtime data display

Fig. 8. Some screen displays in BRMS system

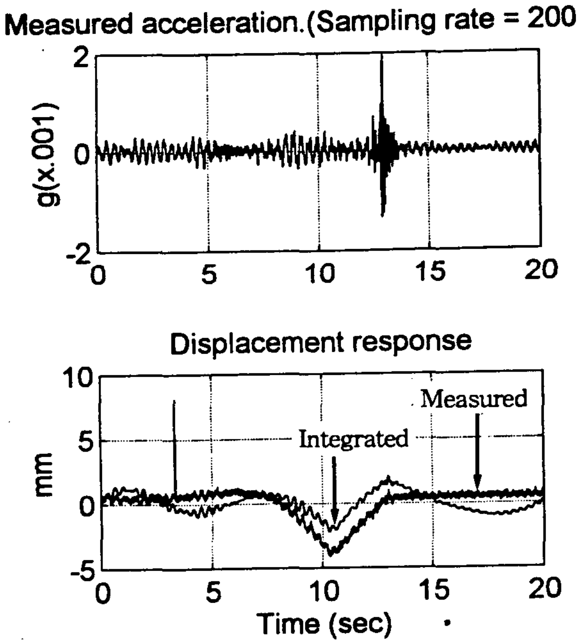


Fig. 9. Example of integrated acceleration data

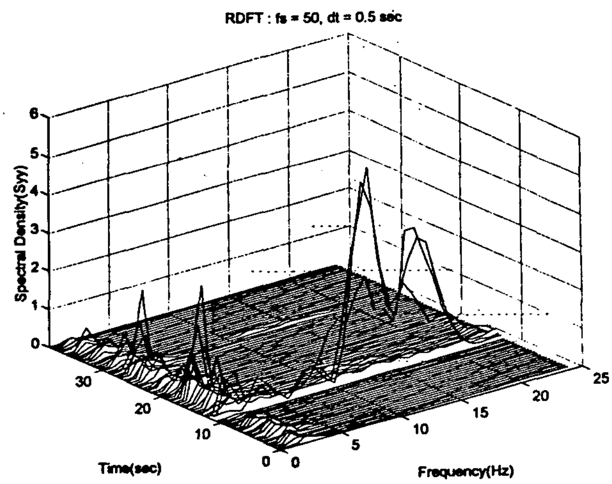


Fig. 10. Real-time FFT spectrum

CONCLUSION

Through load test for the newly introduced precast segmental bridge of external prestressing type, load carrying capacity is evaluated and initial characteristics of bridge is measured for future reference. Results of experimental and analytical evaluation shows that bridge under consideration possesses reasonable margin of safety for code specified design load.

In addition to initial evaluation of bridge by load test, dynamic monitoring system is designed to continuously assess bridge condition. It is considered that proposed remote sensing schemes and some new development for data evaluation method is very promising.

ACKNOWLEDGEMENT

The financial support of Seoul Metropolitan City for this study is greatly acknowledged.

REFERENCES

Aalami, Bijan (1995), "Structural analysis, Ganbyun 1-1 Riverside Highway," Report to SSRC, BFL/Owen, Redwood City, California, USA

Alvarez, R. C. et. al,(1993), "Ten years experience in dynamic testing and assessment of bridges," Bridge managements, Thomas Telford, London.

Guideline for design, construction and maintenance of concrete bridges(1994), Ministry of Construction(in Korean).

Lee, Sung Woo and Bae, Doobyong (1995), "Load test of precast segmental bridge at riverside highway region 1," Research Report, KUM/SSRC-95/10, Structural Safety Research Center, Kookmin University, Seoul, Korea(in Korean).

Lee, Sun Goo and Lee, Sung Woo (to be published)," Integration of measured acceleration to determine the vibration characteristics of bridge," J. of Comp. Struct. Eng. Inst. of Korea(in Korean).

Patric Pautre, Jean Proulx, and Martin Talbt(1995), "Dynamic testing procedures for highway bridge using traffic loads," J. Struc. Eng., Vol 121, No.2, ASCE, P362-396.