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FIELD TESTING OF SEISMICALLY ISOLATED BRIDGE DESIGN BASED ON MINIMUM LCC CONCEPT

Sun Young LEE[1], Hyun-Moo KOH[2], Dong-Ho HA[3], Seung-Yong OK[4], Hyo Sun RYU[5], Hyeong-Taek KANG[6], Young-Suk KIM[7]

SUMMARY

Field testing of a seismically isolated bridge designed according to the minimum LCC concept is conducted for the first time in Korea. The experiment bridge is a 3-span continuous PSC I-girder bridge. The bridge was isolated by widely used seismic isolation bearing, i.e., lead rubber bearing. Quick release testing method using newly developed hydraulic jacks with quick release valves was adopted for the field test.

The quick release test was performed on the bridge with initial displacement of about 55.0mm, which corresponds to 80% of the design displacement. Data interpretation showed that the hydraulic jacks inhibited the initial free vibration of the bridge and, then, reduced its amplitude. Consequently, important information on the nonlinear behavior of the seismic isolators at the initial stage of free vibration could not be observed. Even so, the isolated frequency of the bridge was identified from bridge's free vibration response after total disappearance of the jack force, and the stiffness of the piers were estimated from the measured data during the loading stage. The identified fundamental frequency of the seismically isolated bridge was estimated to be quite higher than the expected one, although the stiffness of piers was identified with reasonable precision. This discrepancy of the isolated frequency is expected to be primarily due to the increase of initial stiffness of the isolators under the in-situ low temperature condition (-10°C)

[1] Ph.D. Student, School of Civil, Urban and Geosystem Engineering, Seoul National University, Korea, Email: sylee@sel.snu.ac.kr *(Presenter)*
[2] Professor, School of Civil, Urban and Geosystem Engineering, Seoul National University, Korea, Email: hmkoh@snu.ac.kr
[3] Assistant Professor, Department of Civil Engineering, Konkuk University, Korea, Email: hadongho@konkuk.ac.kr
[4] Ph.D. Student, School of Civil, Urban and Geosystem Engineering, Seoul National University, Korea, Email: syok@sel.snu.ac.kr
[5] Master Student, School of Civil, Urban and Geosystem Engineering, Seoul National University, Korea, Email: rhs@sel.snu.ac.kr
[6] Researcher, Highway & Transportation Institute, Korea Highway Corporation, Korea, Email: htkang@freeway.co.kr
[7] Researcher, Institute of Research and Development, UNISON Industrial Company, Ltd., Korea, Email: yskim@unison.co.kr

during the test. To verify eventual changes in the characteristics of the isolators, performance tests of the isolators in the laboratory were also carried out after the field test. The results of the repeated performance test showed that the characteristics of the isolators have changed after field test. This kind of variation in the characteristics of isolators has not been reported yet and, thus, its causes will be examined further.
The bridge will be used as a test-bed for various types of seismic protection devices. Although the test results were not entirely satisfactory at this time, subsequent tests will be able to provide reliable data to confirm several design assumptions in the proposed design procedure. The obtained results are expected to provide very valuable information for improving the design specifications of seismically isolated bridges in many countries located in low-to-moderate seismic regions as well as in Korea.

INTRODUCTION

The application of seismic isolation system to bridge has become popular worldwide because of its stable behavior and economical construction. Its excellent performance has been reported and documented through observation of some isolated structures during the 1994 Northridge and 1995 Hyogoken Nanbu earthquakes (Asher [1]). Hence, seismic isolation is now accepted as a well-established technology for the mitigation of seismic damage to bridges. In Korea, the construction of seismically isolated bridge has also increased rapidly for the last five years, though Korea is located in a region of low-to-moderate seismicity.
Since optimal reliability level of isolated bridges can be determined as the one that provides the highest net life-cycle benefit to society, or the minimum Life-Cycle Cost (LCC), an optimal design procedure based on minimum LCC concept is more expedient for the design of seismically isolated bridges. We have already provided a new design concept and cost-effectiveness evaluations based on the LCC analysis for the seismic isolation of bridges (Koh [2]). Studies have reported that a seismic isolation system is more cost-effective in low-to-moderate seismic regions than highly seismic zones. In addition, more flexible isolators are seen to be efficient in such regions. However, the numerous assumptions adopted for analysis and design of such bridge structures have not been validated extensively and thoroughly. In countries with a well-established design code for isolated bridges, these assumptions have been validated on the basis of experimental data and refined analytical models, and behavioral information observed during earthquakes. Therefore, field testing of full-scale structures has been of great interest (Gilani [3], Wendichansky [4], Chen [5], Ronson [6], and Chang [7]). Good examples of successful field investigation were the field tests of the Walnut Creek viaduct in California (Gilani [3]) and the Bai-Ho bridge which is the first application of seismic isolation technology in Taiwan (Chang [7]). In addition, field tests and related analyses were also performed in Korea to experimentally verify the design methods of the seismically isolated bridge and to calibrate analytical models for future analytical correlation and prediction.
Though a new bridge should be constructed for the experimental verification of the presented design concept, an existing bridge, the Nam-Han River Bridge, was selected because of economical and social restrictions. The selected bridge is representative of the expressway bridges in Korea. Since the bridge was constructed in 1971 at a time when seismic design was not applied to bridge structure, the existing bridge bearings were replaced with newly designed lead rubber bearings (LRBs). Quick release testing method was adopted for the test and, accordingly, specially designed hydraulic jacks with quick release valves were newly developed. This paper provides a summary of the test programs, the subsequent data interpretation and numerical analyses that have been and will be performed.

DESIGN OF SEISMIC ISOLATION SYSTEM

Description of Nam-Han River Bridge

The Nam-Han River bridge is located on the Young-dong expressway 71km southeast from Seoul. It has been utilized as a part of Young-dong expressway for about 30 years. A few years ago, a new bridge replaced the old one, which since then, has been left as an emergency roadway. The old bridge has eighteen spans of 540m in total length. The field test was conducted on the eastern 90m portion of the bridge, which is a 3-span continuous viaduct and straight over all its length. The superstructure is a prestressed concrete I-girder structure and the substructure consists of three rectangular single-column piers (P15, P16, and P17) and an abutment (A02), as shown in Figure 1 & 6. The three piers are 10.78m, 8.58m, and 6.78m high, respectively, with the same cross-section (3m×2m). For the field test, all the existing bearings located at the top of piers and abutment were replaced with seismic isolators designed by minimum LCC concept. A total of 30 seismic isolation bearings are installed at three piers and one abutment. Each of the eastern abutment and western pier are isolated by 5 bearings, while the two column bents between them have 10 isolators. This type of bridge representing about 23% of all the expressway bridge stock is one of the most common bridge types in Korea. Therefore, it is expected that the numerical model and the experimental results obtained from the full-scale test of this test bridge will be applicable to a great number of bridges in existence.

(a) An overview

(b) View of girders

(c) View of piers

Figure 1. Nam-Han River bridge

Life-cycle cost minimization

The current design method for the seismic isolation of bridges in regions of high seismicity is based on the strength-based design concept in which the force response of the total system is reduced by lengthening the fundamental period of the bridge and providing additional damping properties. However, in regions of low and moderate seismicity, a design based on such concept may not be an effective design alternative for mitigating seismic damage of bridges. Furthermore, regardless of the level of seismicity, probabilistic approach can be more appropriate in seismic isolation design because earthquake is essentially a probabilistic event. Hence, comprehensive optimization that has a lifetime perspective from design, construction, and maintenance to decommissioning is required (Koh [2]). In addition, since optimal reliability level of isolated bridges can be determined as the one that provides the highest net life-cycle benefit to society, or the minimum Life-Cycle Cost (LCC), an optimal design procedure on the basis of minimum LCC concept is more expedient for the design of seismically isolated bridges.

Total life-cycle cost can be defined as the sum of the initial construction cost and the expected damage cost during a structure's life. Hence, expected value of the life-cycle cost function for a of seismically isolated bridges is defined as follows

$$E\left[C_{total}\left(k_{pier}, k_{iso}, \zeta_{iso}\right)\right] = C_{initial}\left(k_{pier}, k_{iso}, \zeta_{iso}\right) + E\left[C_{damage}\left(k_{pier}, k_{iso}, \zeta_{iso}\right)\right] \tag{1}$$

where $E\left[C_{total}\left(\cdot\right)\right]$ denotes the expected value of the total life-cycle cost, $C_{initial}(\cdot)$ is the initial construction cost, $E\left[C_{damage}(\cdot)\right]$ is the expected damage cost due to failure of the structural system, k_{pier} and k_{iso} are design variables representing the stiffness of pier and isolator, respectively, and damping ratio of isolator ζ_{iso} is also a design variable.

Since the experiment bridge was constructed in 1971, the stiffness of pier becomes an assumed value. Hence, the design variables of the optimization problem reduce to the dynamic properties of the isolator only. Therefore, life-cycle cost function can be reformulated as equation (2).

$$E\left[C_{total}(k_{iso}, \zeta_{iso})\right] = C_{initial} + E\left[C_{damage}(k_{iso}, \zeta_{iso})\right] \tag{2}$$

Since the initial construction cost remains constant in this study, the optimization result represents the minimum failure probability of the isolated bridge subject to earthquakes. Initial construction cost is determined from "Research on Improvement of Bridge Management System (BMS)" (Korea Institute of Construction Technology [8]). Expected damage cost function can be defined by using the design variables and failure probabilities of critical structural components. To compute failure probability, we simply define the failure by the limit states of critical components: unseating of superstructure, local shear failure of isolator, and flexural failure of pier. Since the expected damage cost strongly depends on the level and type of damage at the pier, the failure of a pier is defined as a multi-level damage state. Finally, the expected damage cost function is defined as follows (Koh [9])

$$E\left[C_{damage}(k_{iso}, \zeta_{iso})\right] = \left[\sum_{u=1}^{2} LS_u \cdot P_u(k_{iso}, \zeta_{iso}) + \sum_{k=1}^{5} DS_k \cdot P_k(k_{iso}, \zeta_{iso})\right] \times \frac{\nu}{\lambda}\left(1 - e^{-\lambda t_{life}}\right) \tag{3}$$

$$\lambda = \ln(1+q) \tag{4}$$

where LS_u and P_u are respectively the damage cost and the failure probability induced by failure of superstructure $(u=1)$ or isolator $(u=2)$, DS_k and P_k are also the damage cost and the failure probability of pier in k-th damage state, $q(=4.54\%)$ is discount rate, $\nu(=5\%)$ is occurrence rate of earthquake per one year, and lifetime of the bridge t_{life} is assumed as 50 years.

In this study, a stochastic approach was used to evaluate the expected damage cost of the nonlinear isolation-bridge system. Hence, an acceleration time history for the input ground motion must be generated for nonlinear time history analysis. For that reason, hundreds of artificial earthquake accelerations were generated to perform nonlinear analyses, which will provide reliable earthquake responses.

Design of seismic isolation

For the design of seismic isolators, the experiment bridge was modeled as 2DOF system, as illustrated in Figure 2. Seismic isolator and pier were modeled as equivalent linear model and bilinear model, respectively. The structural properties are listed in Table 1.

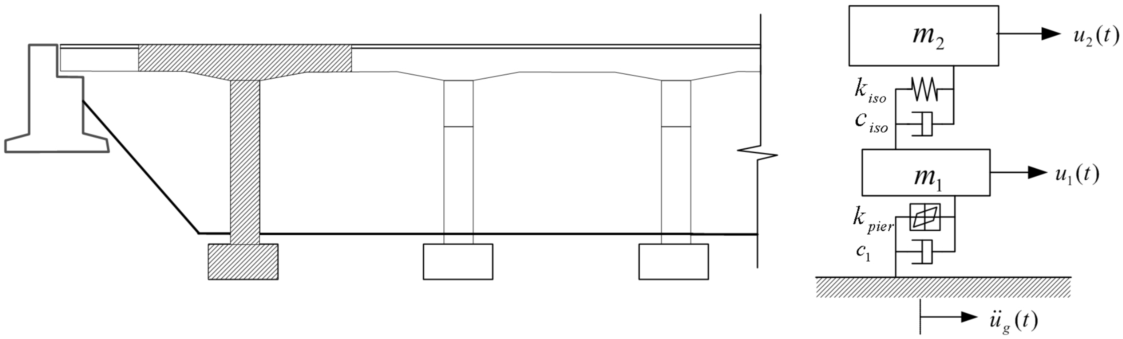


Figure 2. 2DOF model of seismically isolated bridge

Table 1. Properties of the 2DOF structure

Superstructure mass per pier	544.1 *ton*	Effective mass of pier	159.7 *ton*
Stiffness of pier	$1.08\times10^5\ kN/m$	Damping ratio of pier	2.00 %
Reinforcement ratio of pier	1.03 %	Yield displacement of pier	22.2 *mm*

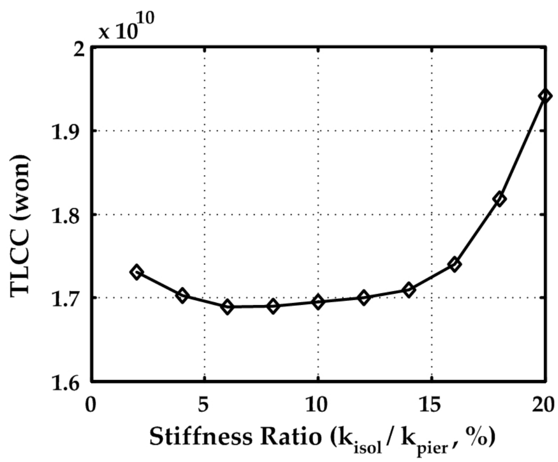


Figure 3. Optimization result

Figure 3 shows the optimized stiffness ratios resulting from the stochastic approach. The LRB's optimal dynamic properties are the equivalent stiffness and damping ratio of 655.42*kN/m* and 25.0%, respectively. Following, the isolated period of the designed bridge is estimated to lengthen from 0.89sec to about 1.90sec, and the design displacement 68.0*mm* is obtained for the bridge.

TEST PROGRAM AND RESULTS

Performance Test of Bearings

Before the LRBs were applied to the bridge, laboratory tests with a series of cyclic loadings were conducted to ensure that the characteristics of the bearings met the required performances. For the performance test, several cycles of lateral displacement reversals, in which the maximum displacement value were set to the design displacement of the bearings, were carried out under the design dead load. Figure 4 shows the hysteretic behavior from the cyclic loading test of one of the manufactured LRBs. Dynamic characteristics of the bearings were obtained by using nonlinear curve fitting method, which will be used later for numerical models.

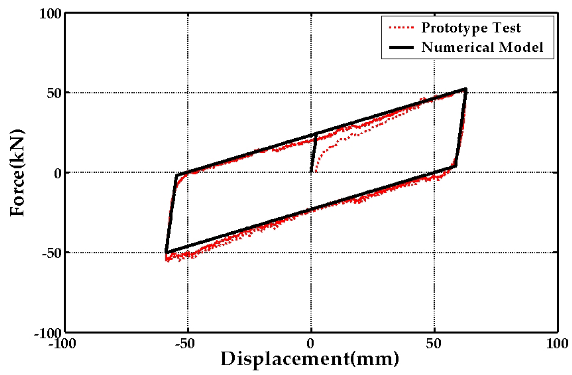


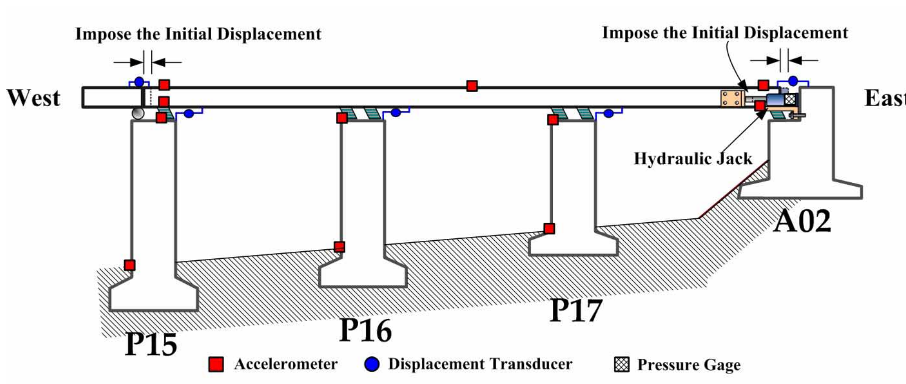
Figure 4. Hysteretic behavior of LRB

Free Vibration Test

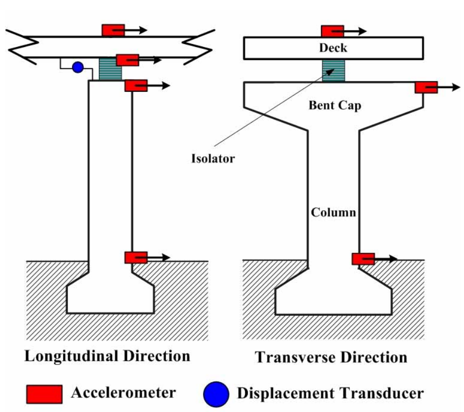
The free vibration tests were conducted by pushing the bridge deck along its longitudinal axis using two hydraulic jacks with its full load capacity of 2,000kN and maximum stroke of 150mm, as shown in Figure 5. Since the abutment had enough capacity to provide the necessary resistance to jacking forces for the test, it was used as a supporting wall of the hydraulic jack to push the bridge deck. In order to transmit the jacking force to the bridge deck, specially designed steel brackets were attached to the webs of the concrete girders.

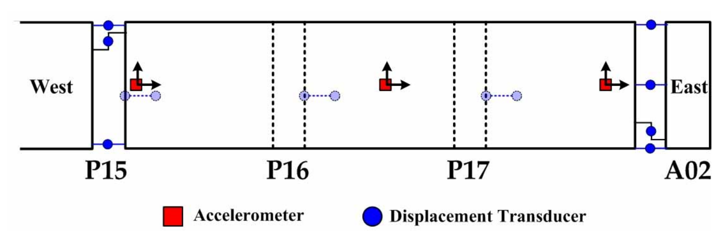
Figure 5. View of a hydraulic jack

Instrumentation for the free vibration tests consisted of 27 data channels with 16 accelerometers, 10 displacement transducers and a pressure gage. Figure 6 shows the layout of the instrumentation for the test. Used to determine the natural frequency and mode shape of the bridge, accelerometers were installed at the deck level, the girder level, the top of the bent cap, and the ground level of pier in both longitudinal and transverse directions. The pressure gage was placed in the hydraulic jack system to record the total applied load. Four displacement transducers were installed at the top of three piers and one abutment to measure the relative displacement of isolators. Moreover, four displacement transducers were placed at the four corners of the deck to monitor the absolute displacement of superstructure, and two displacement transducers were also installed in the transverse direction to check the twisting effect of the loading.



(a) Side view of instrumentation layout





(b) Instrumentation of typical bent

(c) Instrumentation of deck

Figure 6. Instrumentation layout for the free vibration test

The quick release test was performed on the bridge with initial displacement of about 55.0mm, which corresponds to 80% of the design displacement. The imposed displacement is seen to exceed by far the LRB's yielding point obtained from performance tests. A typical measured displacement response of LRB is shown in Figure 7. The acceleration responses measured at the deck and top of the pier were compared and plotted, as shown in Figure 8. A discontinuous interval appears in the acceleration time history and very small peak values in the vibration response are observed in the displacement time history. This phenomenon can be explained by the fact that the hydraulic jacks inhibited the dynamic motion of the deck. The jacks were originally designed so that the oil pressure vanishes within 0.2sec after release of the valves since the deck is expected to enter in motion 0.25sec after the release from the simulated result of the quick release test. In the test, however, the test bridge showed higher stiffness than expected, which initiated the motion faster. Hence, the nonlinear behavior of the seismic isolators at the initial stage of free vibration could not be captured. Nevertheless, the comparison of peak accelerations between the top of the pier and the deck demonstrated the isolation effects of the seismic bearings even if there was a small difference between the peaks.

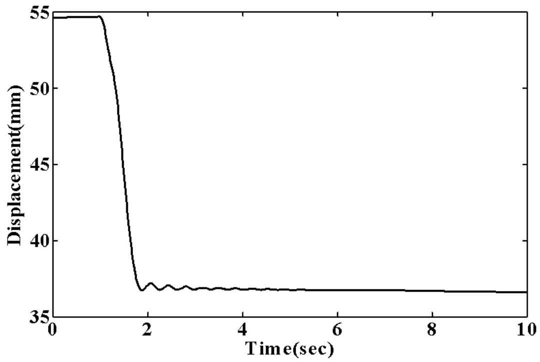


Figure 7. A typical measured displacement response of the LRB

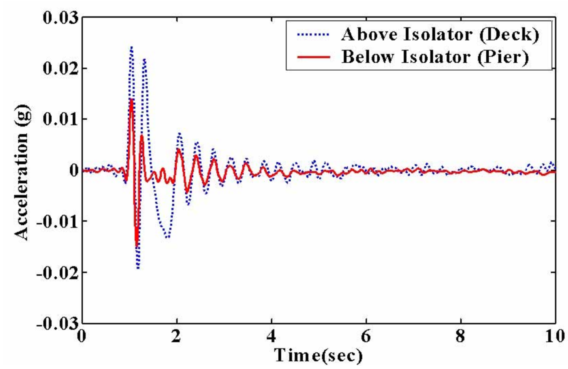


Figure 8. Acceleration time history at the deck and the top of the pier

Even though the measured data were distorted due to disturbance of hydraulic jack against the recovery motion of the bridge deck, we identified dynamic properties of the bridge such as isolated frequency, damping ratio, and mode shape. Considering the disturbance effect of the jack, the frequency response of the bridge is obtained by using the latter part of the acceleration responses only, which corresponds to the free vibration response of the bridge after the jack force totally disappeared. Longitudinal frequency responses of the bridge under the free vibration test are illustrated in Figure 9. The frequency of the isolated mode is approximately equal to 2.75Hz in longitudinal direction. This value is quite different from the target design frequency, about 0.53Hz. The difference is due to the fact that the quick release vibration of the bridge does not repeat the full cycle of the isolator's hysteretic loop. In the quick release test, hysteretic behavior of isolators only happened within one fourth cycle of the hysteretic loop (Chen [5]). In the one-fourth cycle of the hysteretic loop, the total quick-release response of the seismically isolated bridge consists of two distinct parts, an initial non-linear portion and the elastic tail. The nonlinear part corresponds to the initial half-cycle of the displacement response and the elastic tail, corresponding to the succeeding free vibrations, is represented by the initial stiffness of the isolators. Therefore, the isolated frequency largely depended on the initial stiffness of the isolation bearings. Moreover, the field test with 80% of design displacement shortened the fundamental period of the bridge.

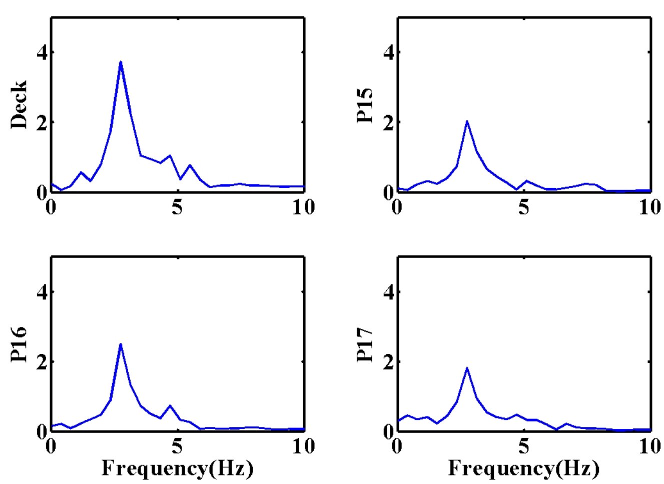
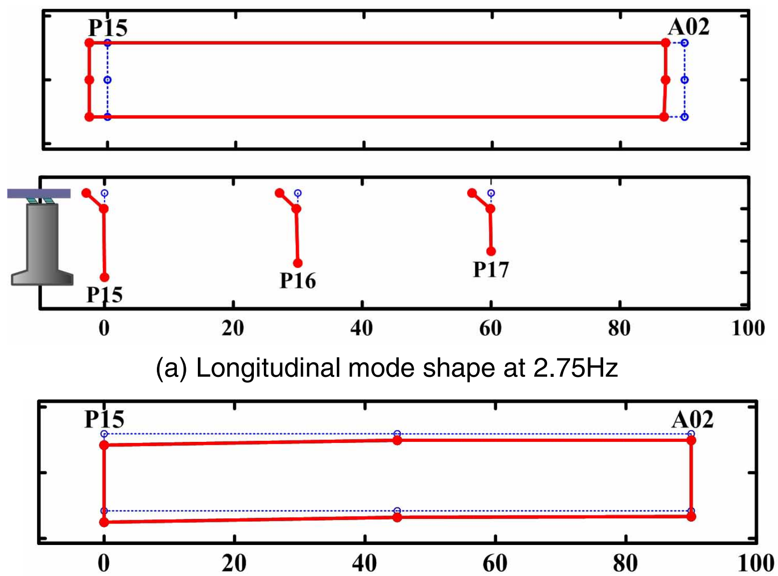


Figure 9. Longitudinal frequency response of the bridge

Equivalent viscous damping ratio is also calculated by using the latter part of the deck acceleration responses. To obtain the damping properties of the isolated mode, the isolated modal response is extracted by using filtering techniques. Then, the negative exponential sinusoidal functions are fitted to the data. By using the nonlinear curve fitting method, the obtained damping ratio was evaluated as about 8% for the isolated mode.
In transverse direction, the first vibration frequency was determined to be 5.76Hz. Using the amplitudes of the frequency responses corresponding to modal frequency, the longitudinal and transverse mode shapes of the superstructure under free vibration were obtained; these shapes are portrayed in Figure 10.



(a) Longitudinal mode shape at 2.75Hz

(b) Transverse mode shape at 5.76 Hz

Figure 10. Longitudinal and transverse mode shapes of the bridge

The stiffness of piers was identified from the measured data during the loading stage. Since jack forces are applied very slowly in an essentially static manner during the loading stage of the tests, the dynamic effects can be neglected. Therefore, global jack force can be distributed to the bents according to bent stiffness. However, since the columns are stiffer than the isolators for large deformations, the total lateral force may be approximately divided among the bents according to relative stiffness of the isolators at various bents. From this approximation, the lateral forces of isolators and columns can be calculated. Figure 11 shows the hysteretic behaviors of pier 15, 16, and 17, respectively. Dotted red lines represent the numerical results using the products of pier stiffness and measured pier displacement, and blue lines shows the relations between pier displacement and divided jack force. Although the stiffness values of pier 16 and 17 slightly decrease, stiffness of pier 15 is slightly higher than that from the numerical model. It is estimated from the result that the roller bearings of adjacent bridge section located at pier 15 increased the stiffness of the pier by acting as a friction bearing. Since the bridge was constructed about 30 years ago, its roller bearings have been deteriorated.

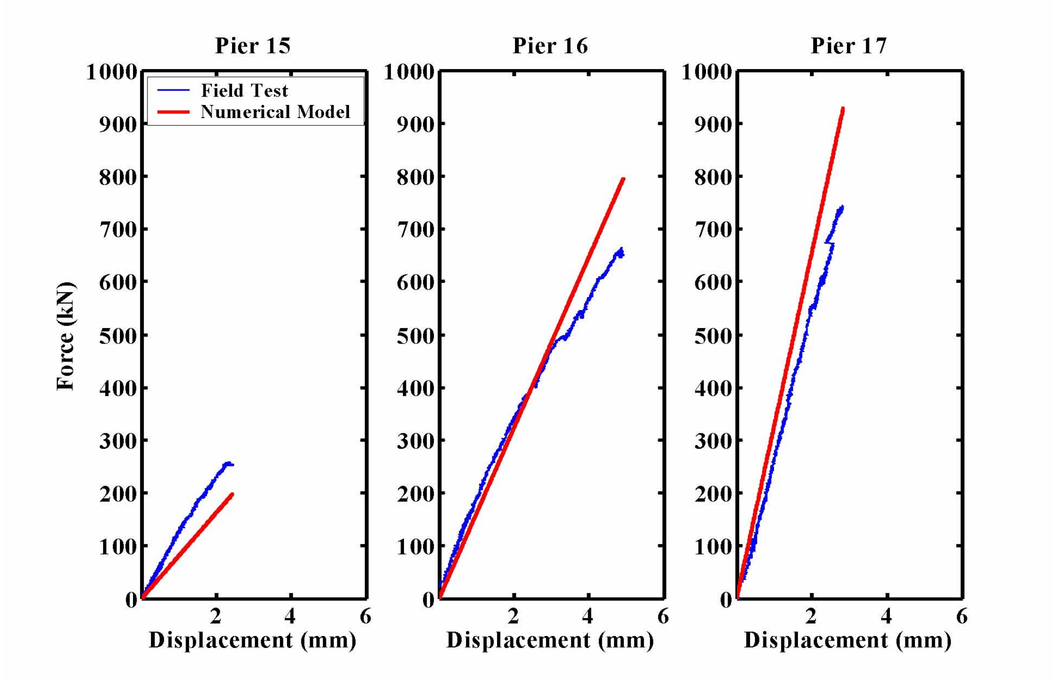


Figure 11. Hysteretic behaviors of pier 15, 16 and 17

The natural frequency 2.75Hz of the isolated mode was identified to be higher than the estimated value obtained from the preliminary simulation. To verify the increased frequency stiffness, LRBs were removed from the test bridge after field test and the performance test in the laboratory was repeated. The repeated test result in Figure 12 showed that the characteristics of the isolators were significantly altered after the field test. The averages of the effective stiffness, initial stiffness and post-yield stiffness of the isolators increased by about 17%, 29%, and 19%, respectively. This kind of variation in the characteristics of isolators has not been reported to date and more examination should be performed to find its causes.

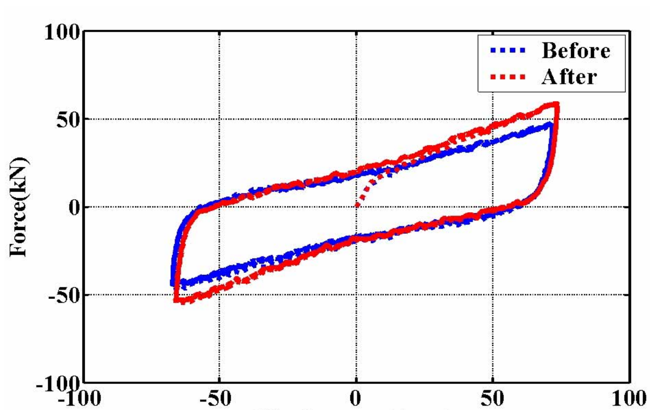


Figure 12. Variation of hysteretic behavior of isolators after field test

NUMERICAL ANALYSIS

Using all the dynamic properties obtained from the test, a numerical model was constructed as 4-DOF nonlinear model, as shown in Figure 13. In this model, the piers are modeled as linear elastic spring elements and linear viscous damping elements, and the isolators are modeled as bilinear hysteresis models and linear viscous damping models. Simulations of the free vibration test were carried out on the numerical model with the initial displacement of 55mm. Figure 14 shows the comparison results of the experimental and simulated responses. The free vibration behaviors of the isolated bridge were quite different from the measured responses of the test. The displacement and acceleration responses from the free vibration of the bridge were distorted due to disturbance of the hydraulic jack against the recovery motion of the bridge deck. Therefore, the simulated results did not coincide with the test results. However, the frequency contents of the free vibration showed slight difference in the isolated frequency corresponding to the peak value of frequency responses. This discrepancy of the isolated frequency is estimated to be mainly due to the increased initial stiffness of LRB under low temperature condition, as seen in Figure 14. More detailed evaluation on nonlinear dynamic properties of the isolated bridge system will be performed further.

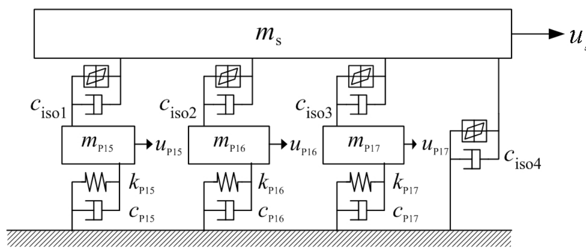


Figure 13. 4 DOF nonlinear model of the test bridge

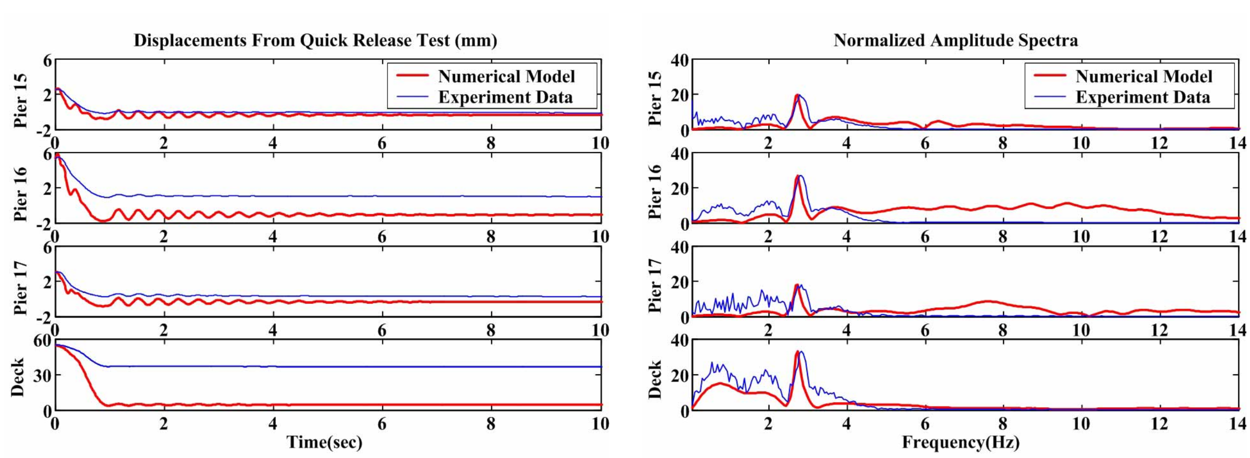


Figure 14. Comparison result of simulated results and test data

CONCLUSIONS

The application of seismic isolation system has become popular worldwide because of its stable behavior and economical construction especially for bridge structures. In Korea, the use of seismic isolation systems is now recognized as an effective and economical seismic design alternative related to optimization with respect to lifetime of the structure, considering low and moderate seismicity. This paper focuses on experimental verification to confirm a new design methodology for structures on the basis of minimum LCC concept in low and moderate seismicity regions.

The experiment bridge was the Nam-Han River bridge which is an 18-span continuous PSC I-girder bridge located on a closed highway. The first continuous 3-span, 90m portion of the bridge was tested with quick release testing method. Specially designed hydraulic jacks with quick release valves were newly developed for the test. The experiment bridge is isolated by using widely used seismic isolation bearing, i.e., lead rubber bearing.

The quick release test was performed on the bridge with initial displacement of about 55.0mm, which corresponds to 80% of the design displacement. Data interpretation showed that the hydraulic jacks inhibited the initial free vibration of the bridge and, then, reduced its amplitude. Consequently, important information on the nonlinear behavior of the seismic isolators at the initial stage of free vibration could not be observed. Even so, the isolated frequency of the bridge was identified from free vibration response after jack force totally disappeared, and the stiffness of the piers was estimated from the measured data during the loading stage. The identified fundamental frequency of the seismically isolated bridge was estimated to be quite higher than the expected value, although the stiffness of piers was estimated with reasonable precision. To verify the eventual changes in the characteristics of the isolators, performance tests in laboratory were also carried out after the field test. The repeated test result showed that the characteristics of the isolators have changed greatly after the field test. This kind of variation in the characteristics of isolators has not been reported yet and, thus, more examination to find the causes of the variation will be performed in the future. Numerical analysis was performed by using dynamic properties obtained from the field test. Although the simulated responses showed some differences with recorded results in time domain, we could establish a numerical model with similar frequency contents. However, there still remains some difference in isolated frequency of the bridge. The minor disagreement of the isolated frequency is expected to be primarily due to the increase of the initial stiffness of the isolators under the in-situ low temperature condition (-10°C) during the test. Therefore, further examination will be performed later.

The bridge will be used as a test-bed for various kinds of seismic protection devices. Although the test results were not entirely satisfactory at this time, subsequent tests that will be improved significantly on the basis of these results and experiences will be able to provide reliable data to confirm several design assumptions in the proposed design procedure. The developed numerical model also will be a useful tool in continuing tests. The obtained results are expected to be very valuable information for improving the design specifications of seismically isolated bridges in many countries located in low-to-moderate seismic regions as well as in Korea.

ACKNOWLEDGEMENTS

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