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Static and Dynamic Calibration of a Suspension Bridge Model for Structural Assessment

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ABSTRACT

The assessment of suspension bridges often combines the findings from field inspections and tests with careful computer modeling in order to arrive at a complete picture of the structure's condition. This paper describes the calibration of the computer model of the Nam Hae Grand Suspension Bridge in Korea's Kyongsangnam-do Province. This 660 m long bridge was instrumented with tilt meters and survey targets in order to obtain deformations under static loads. The results from the static tests and earlier dynamic test results were used to verify a three dimensional computer model of the structure. This model was subsequently used to carry out wind and traffic load studies as well as a seismic study of the bridge.

INTRODUCTION

A general view of the Nam Hae Grand Bridge is provided in Fig. 1. The Nam Hae Grand Bridge connects Nam Hae Island with Hadong on the Korean Mainland in the Province of Kyongsangnam-do. It is a three span suspension bridge with a main span length of 404 m and side spans of 128 m each. The two 60 m high towers are founded on concrete caissons. The main cables have a diameter of 258 mm and are made of parallel wire and the hangers are made of 47.5 mm diameter bridge strand. The stiffening system consists of a welded steel box girder with an orthotropic steel deck. A typical cross-section of the 12 m wide and 1.6 m high box girder is shown in Fig 2. The top flange is made of 11 mm plate stiffened by twelve 230 mm deep troughs of 8 mm thickness. The 7.2 m wide two lane roadway has an asphalt wearing surface. The bridge was constructed by Ishikawajima-Harima Heavy Industries Co Ltd. (IHI) of Japan. Construction was completed in May 1973 (IHI 1973).

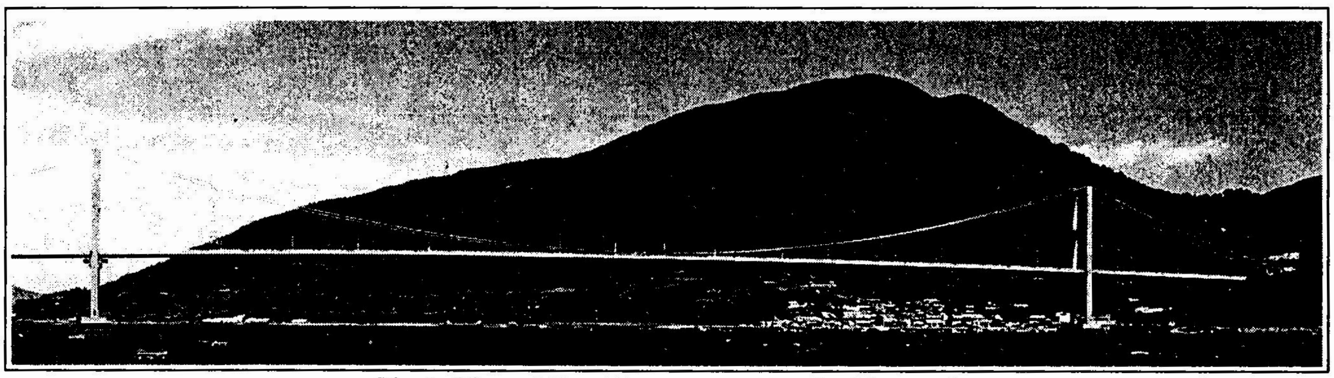

Fig. 1: View of Nam Hae Grand Bridge (looking east)

In the spring of 1996 Buckland & Taylor Ltd. (B&T) was retained by Hyundai Engineering and Construction Co. Ltd. (HDEC) to inspect and evaluate the Nam Hae Grand Bridge. The field inspection was carried out by the authors and additional field work, including the static testing, was carried out by HDEC personel and/or agents while the modeling and evaluation of the bridge was carried out by B&T. This paper describes the results of both static and dynamic tests which were carried out on the structure and then used to verify the computer model of the Nam Hae Grand Bridge.Once the computer model was verified, it was used to evaluate the bridge using criteria based on the 1996 edition of the Korean Bridge Design Code.

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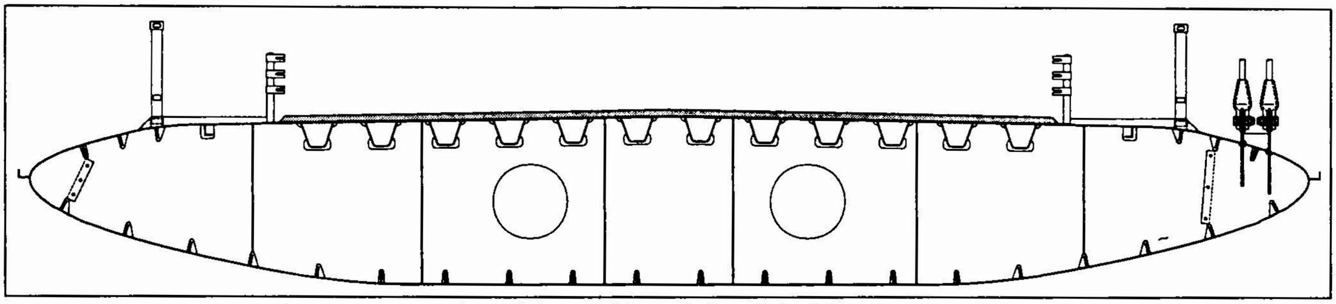

Fig. 2: Cross-section of the steel box girder of the Nam Hae Grand Bridge

COMPUTER MODELING

The Nam Hae Grand Bridge was idealized using the 3D spine model shown in Fig. 3. This model was solved using the finite element program CAMIL (Buckland & Taylor Ltd. 1996). The model was created using 346 beam elements and 210 non-linear cable elements. The box girder was modeled using three spine beams and stiff outriggers. The properties of the members were selected to model the bending and torsional stiffnesses of the box as well as the location of the center of mass and the mass moment of inertia. The massive caisson foundations under the towers were modeled as rigid supports. In addition, the splay saddles of the anchorages were modeled as points of cable fixity.

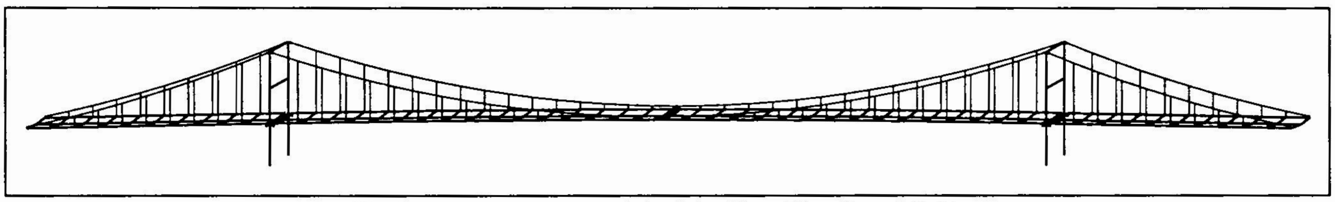

Fig. 3: 3D Computer model of the Nam Hae Grand Bridge

STATIC TESTING

During the inspection of the bridge, Buckland & Taylor Ltd. provided objectives for a static test of the bridge which would be used to calibrate the computer model. The test planning, selection of instrumentation and test execution were carried out by HDEC and its agents. The test required the complete closure of the bridge and therefore had to carried out in the early morning hours of 1996 June 19. During the test, not all the data which was desired at the planning stage was collected due to instrumentation problems. However, the data was sufficient to carry out the model verification.

Test Objective

The objective of the survey was to determine the geometry of the bridge at the following three stages:

- self weight (Unload 1)
- self weight and two trucks of known weight (Load)
- self weight after removal of trucks (Unload 2)

Loading Trucks

The bridge was loaded with two trucks weighing 258 kN each. Both trucks had an axle spacing of 3.6 m from the front axle to the first rear axle and 1.35 m between the rear axles. The trucks were planned to be placed facing south with their front axles aligned with hanger number 25 (mid span) and hanger number 17 (quarter span) as shown in Fig. 4. The trucks were placed 0.3 m from the east or west guard rail.

Test Instrumentation

Survey prism targets were attached to all the hanger bands on the main cable and to every second hanger pin at the deck level. The locations of targets on the east side of the bridge are shown in Fig. 5. A similar set of targets was installed on the west side of the bridge. The targets were vertically and longitudinally aligned with the centre of the hanger pins at deck level, and at the intersections of the centerlines of the main cable and the hangers. In addition, three targets were installed on the east and west side of each tower. The three targets were located at the base of each tower, at deck level and at the top of the tower. A common point, visible from both sides of the bridge, was set up near the base of the Nam Hae tower and

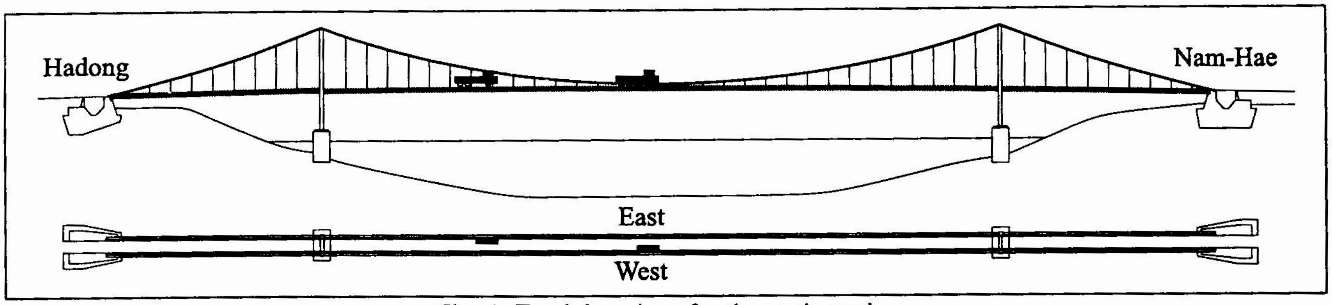

Fig. 4: Truck locations for the static testing

additional references were installed on the Hadong anchorage and on the tower foundations. The locations of the common and reference points were not determined with reference to known locations which could be identified on the original drawings of the bridge, but were intended to tie together the measurements taken from instruments on the two sides of the bridge. The survey instruments used were programmed to automatically locate and electronically record each target in rapid succession.

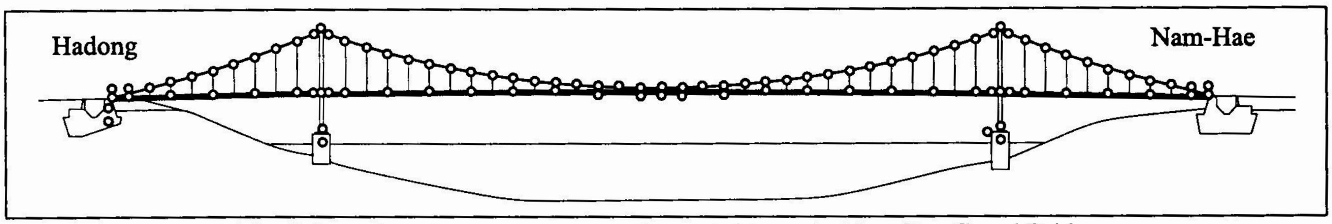

Fig. 5: Location of survey targets on the east side of the Nam Hae Grand Bridge

Six bi-axial tiltmeters were installed on the main span deck. As shown in Fig. 6, tiltmeters 1 and 2 were installed at the center of the deck near the towers, while the remaining tiltmeters 3, 4, 5, and 6 were installed in pairs on either side of the deck at mid-span and the quarter span. Tiltmeter readings were taken every minute from 3:00 am to 5:49 am.

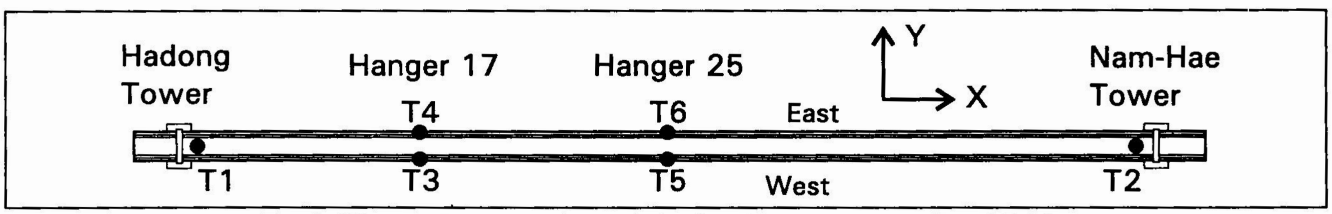

Fig. 6: Tiltmeter Locations for static load testing of Nam Hae Grand Bridge

Surface temperature readings were taken near both anchorages, at the top of both towers and at mid span. The temperatures were recorded every 5 minutes from 3:40 am to 6:40 am.

The wind speed was measured near the center of the main span. This data was also recorded every 5 minutes from 3:40 am to 6:40 am.

Static Load Test Result

Temperature Data: Of the five temperature sensors, only the two sensors located near the anchorages provided readings for the entire test period. At the Nam-Hae Anchorage the measured temperature varied from 19.3 to 20.7 °C, while at the Hadong anchorage it varied from 18.3 to 19.4 °C. The temperature variations for the other three locations were; Hadong Tower 18.0 to19.0 °C, Nam Hae Tower 17.2 to 19.2 °C, and Main span 18.1 to 19.3 °C.

Wind Speed Data: The wind speed was in the order of 4 m/s at the beginning and at the end of the test. During the truck loading period the wind speed was less than 2 m/s.

Tiltmeter Data: The tiltmeter data given in Table 1 shows the tiltmeter readings at three times representing the three stages of the test. As can be seen from the data the tilt readings for the two unloaded conditions is not quite identical. This may be due to wind loading, thermal changes in the structure or data acquisition errors.

Table 1: Tiltmeter Readings

CHANNEL	Tilt [micro radians]				
	Unload1 (4:00 am)	Load (5:00 am)	Unload2 (5.45 am)	Load - Unload1	Load - Unload2
1X, 1Y	32.65, 34.57	2028.78, 227.83	-57.88, 71.89	1996, 193	2086, 156
2X, 2Y	61.69, -20.17	2251.66, -87.59	109.30, -51.41	2190, -67	2142, -36
3X, 3Y	-8.46, -5.05	958.62, 561.46	-79.25, -6.61	967, 567	1038, 568
4X, 4Y	-16.21, -72.26	761.63, 295.55	-75.01, -69.37	778, 368	831, 365
5X[a], 5Y	N/A, -13.40	N/A, -564.97	N/A, 7.59	N/A, -552	N/A, -573
6X, 6Y	-62.93, -53.11	-2264.93, -668.14	-19.21, -92.86	-2202, -615	-2245, -575

a. This channel saturated during the entire test

Survey Data: As mentioned above, theodolites were set up at one station on each side of the bridge and automated readings of the targets were taken in several sweeps. The survey of the points on the east side of the bridge was mostly but not fully complete. No common points were measured with respect to both stations, hence the data from the two stations cannot be combined without assumptions about the bridge geometry. Most of the main cable was not measured before the loading of the bridge (Unload 1). However after the load was removed (Unload 2), a complete survey of unloaded cable geometry was obtained. The survey for the west side yielded only very sparse results because of instrumentation problems.

COMPARISON OF COMPUTER MODEL AND STATIC LOAD TEST RESULTS

Deck Deflections

The deflections of the bridge under the test truck loads were computed using the 3D spine model. From the survey information, the difference between vertical coordinates was obtained from the second unloaded state (Unload 2) and the loaded state (Load). The computed deflections of the east side of the bridge are shown in Fig. 7 as a solid line. The same figure shows the deflections obtained from the survey as '+' symbols. The initial correlation is not ideal in the quarter span to mid-span region. However, changing the orientation of the 1/4 span truck from facing Nam Hae to facing Hadong with the front wheel at the same location produced extremely close correlation between measured and computed deflections. Further investigation into the 1/4 span truck's location revealed that its orientation was not recorded during the test and could not be conclusively established afterwards. Overall, considering the sensitivity of the deflections to the exact location and orientation of the trucks, the correlation in Fig. 7 is very satisfactory.

Deck Rotations

The measured rotations obtained by the tiltmeters were compared to the rotations computed using the 3D spine model. When comparing the measured and computed tilts one must consider that the measured tilts include local deformations of the deck of the box girder while the computed tilts only model the global deformations of the box section. These local deformations affect the readings of the sensors (3, 4, 5, and 6) near the trucks the most. The comparison between X-tilt (Longitudinal) and the computed rotations is given in Fig. 8. This figure shows that the rotations at the two ends of the main span (sensors 1 & 2) are in good agreement. The measured X-tilt near the quarter span (sensors 3 & 4) also shows reasonable agreement with the computed rotations. Of the two tilt meters in the center of the deck (sensors 5&6), only sensor 6 provided X-tilt data. This data also compares well with the computed rotations.

The measured Y-tilt (Transverse) and the computed rotations are given in Fig. 9. The computer model predicts very small rotations in the order of 10 micro radians at the ends of the deck. However, the measurements indicate that rotation in the order of 200 micro radians occurred near the Hadong Tower (sensor 1). These larger measured rotations could be the result of slightly misaligned instruments. Since the X-tilts (Longitudinal Tilt, sensor 1&2) are in the order of 2000 micro radians, a sensor misalignment of less than 6 degrees would result in cross axis pickup of more than 200 micro radians.

The transverse tilt computed at the quarter span is lower than that measured at sensor 3 and higher than that measured at sensor 4. This is most likely due to local deformations of deck near the truck which were not modeled. As the precise locations of the sensors were not documented, no estimates of local deformations could be made. At the mid span, the mea-

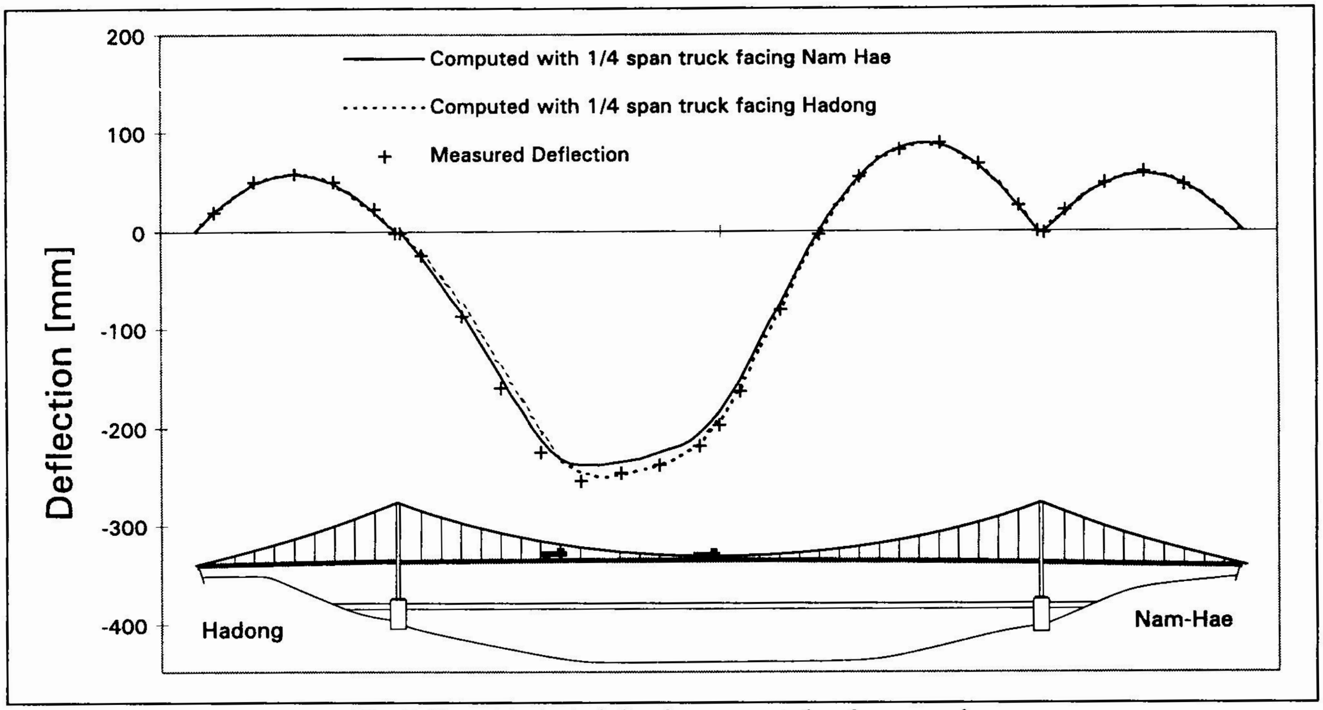

Fig. 7: East side deck deflection computed and measured.

sured tilts (sensors 5 & 6) are only about 60% of the computed ones. At this location, it is also possible to infer the tilt of the deck from the east and west side survey. Using this approach, a rotation of -741 micro radians was determined. This value lies approximately half way between the rotations obtained from the tiltmeters and those obtained from the computer model.

In general, given the uncertainties regard to sensor orientation and location, a satisfactory correlation between the measured and computed tilts was obtained.

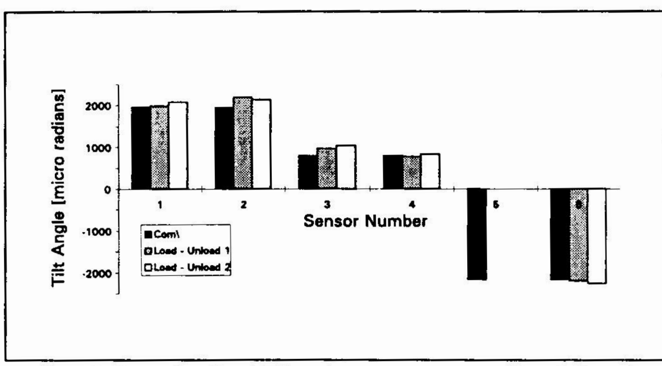

Fig. 8: Longitudinal Tilt of the Deck under Truck Load

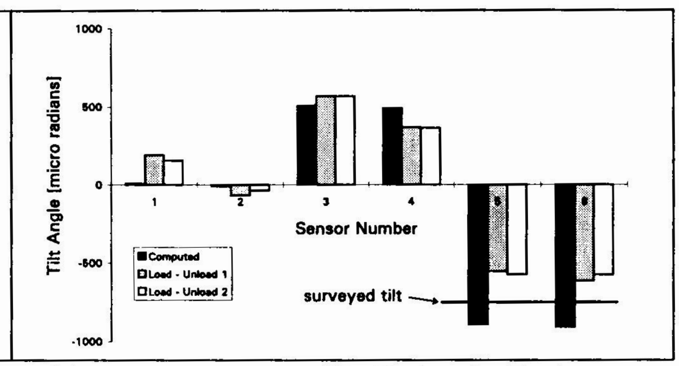

Fig. 9: Transverse Tilt of the Deck under Truck Load

DYNAMIC TEST DATA

As part of an earlier (Korean Ministry of Infrastructure and Construction 1993) evaluation study, ambient vibration measurements were conducted. The dynamic characteristics obtained from these measurements were reviewed and the identified vertical and torsional frequencies of the deck were selected for correlation purposes.

CORRELATION WITH DYNAMIC TEST DATA

The dynamic characteristics of the bridge predicted by the computer model are compared to the ambient vibration test results in Table 2. The table shows the natural frequencies obtained from two different computer models. The first model includes the traction rod assembly at mid span. The traction rod assembly restrains longitudinal movemnt of the deck relative to the main cables with two inclined struts per side which connect the deck to the central hanger band of each main cable. The second model does not include the traction rod assembly. During the field inspection, it was observed that the pins of the traction rods were worn and thus the traction rods may not be effective during the small amplitudes of motion associated with ambient measurements. Therefore, it is not surprising that the computer model without traction rods gives better agreement with the measured results for the antisymmetric vertical modes (which are affected by traction rods). The good agreement between the measured and computed values validates the computer model's ability to predict the vertical and torsional modes of the structure.

For the subsequent dynamic analysis under earthquake loading, the model with traction rods was used (as the associated displacements quickly take up the slack in the pins). The model without the traction rods was used to assess the magnitude of displacements which might occur in the event of a traction rod failure during an earthquake.

Table 2: Computed and Measured Natural Frequencies of the Nam Hae Grand Bridge

Mode Shape	Frequency in [Hz]		
	Model Without Traction Rods	Model With Traction Rods	Ambient Test
V1_A[a]	0.229	0.209	0.228
V2_S	0.255	0.255	0.251
V3_S	0.362	0.362	0.359
V4_A	0.395	0.383	0.391
V5_S	0.520	0.520	0.514
V6_A	0.533	0.530	0.523
V7_S	0.751	0.751	0.731
T1_S	1.013	1.013	0.982
T2_A	1.705	1.705	1.643
T3_S	2.578	2.578	2.446

a. V# = vertical mode, T#= torsional mode, _A= anti-symmetric, _S= symmetric

CONCLUSIONS

The three dimensional spine model of the Nam Hae Grand Bridge was verified using the results from both static vertical loading tests as well as low level ambient vibration measurements. The carefully constructed computer model showed good agreement with the test results and the model could subsequently be used with greater confidence to predict the response of the structure under vehicular live load as well as wind and earthquake loading.

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