Analysis of Structural Health Monitoring data for the cable-stayed bridge with ruptured cables

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ABSTRACT: The Seohae Bridge is the 7.31km long sea crossing bridge and composed of a cable-stayed bridge and a pre-stressed concrete box girder bridge. The steel-concrete composite cable stayed bridge is 990m-long and consists of three cable-stayed spans of 200m + 470m + 200m and two 60m-long end spans. The cable-stayed span is supported by 144 cables and equipped with a Structural Health Monitoring System (SHMS) to monitor critical structural elements. The SHMS has 97 sensors including GNSS sensors, accelerometers, tiltmeters, and strain gauges. The System was initially installed in 2000 when the Bridge was constructed and renovated in 2009. It has provided information on the structural behavior and safety of the cable stayed bridge. On December 3, 2015, one of longest stay cables caught a fire near cable-pylon anchorage zone. The fire caused by lightning strike lead to complete rupture of one stay cable and partial rupture of two more stay cables. Damaged cables were quickly replaced within 15 days after the fire. Rupture of the cables affected the overall structural systems of the cable-stayed bridge. In this paper, the changes in structural systems were analyzed using data from the SHMS.

I SEOHAE BRIDGE
The Seohae Bridge, which opened to traffic in November 2000, is located approximately 65 km south of Seoul and is one of the longest cable-supported bridges in Korea. The total length of the bridge is 7.31 km and it consists of a cable-stayed bridge and two different types of pre-stressed...
concrete (PSC) box-girder bridges. The cable-stayed bridge, which is 990-m long, consists of three cable-stayed spans of 200 m + 470 m + 200 m and two 60-m long end spans of simply-supported composite girders (Figure 1). The deck cross section consists of two longitudinal steel girders spaced 34-m apart, with steel floor beams between these edge girders at 4.1 m on center, and precast concrete panels. The two pylons are H-shaped concrete structures that reach 186-m above sea level. The three cable-stayed spans are supported by two planes of stay cables each plane contains 72 cables. The length of stay cables ranges from 54 to 228 m. The stay cables are numbered from 1 to 72, left to right. These cables are made up of seven-wire strands with diameters of 15.2 mm. The strands are galvanized, covered by wax, individually sheathed, and placed inside a high density polyethylene (HDPE) pipe without grout.

2 STRUCTURAL HEALTH MONITORING SYSTEM

To monitor the structural response and evaluate the performance of the Seohae Bridge, the structural health monitoring system, called the Seohae Structural Health Monitoring System (SSHMS), was installed in the year 2000. The specified objectives of the SSHMS were (1) to monitor the structural response and evaluate the performance of the bridge, (2) to provide required information to the Bridge Management System (BMS), and (3) to provide useful information for design, construction, and maintenance of similar types of bridges. Many sensory instruments, such as anemometers, accelerometers, tiltmeters, strain gauges, and temperature sensors, were placed in locations where the overall structural behavior and performance of the critical members could be easily determined. After the test operation period in 2001, the Bridge had been continuously monitored. In 2009, the SSHMS was totally renovated due to the deterioration of hardware such as the sensors and data loggers and software (Gil et al, 2010). Most of the existing sensors such as accelerometers, temperature sensors, and tiltmeters were replaced during renovation. A real-time kinematic (RTK) GNSS (Global Navigational Satellite System) monitoring system was installed to monitor the static and dynamic behavior of the Bridge. An internet-based program to monitor the real-time behavior of the bridge system and to manage data was also developed that integrates the latest developments in data base

Figure 2. Sensor layout for the SSHMS.
management and web technology. As shown in Figure 2, the SSHMS has currently 97 sensors and continuously monitors structural integrity of the Bridge.

3 LIGHTNING STRIKE, FIRE AND RECOVERY

During winter thunderstorm on the evening of December 3, 2015, one of the longest upper cables in the downstream side of the deck, 72D, caused a fire. The fire started almost 80m above the bridge deck and lasted more than two hours. Fire fighters arrived at the scene of the cable fire but they were unable to quickly control the fire because of strong wind and height of fire source. As fire progressed, the 72D cable was completely severed. About two-thirds of the 72D cable dropped on the top of the bridge deck while the remaining one-third cable was dangled from the pylon anchorage as shown in Figure 3. The remaining 72D cable was still under the fire and lead to fire of two more cables in the downstream cable plane, a 56th (56D) cable and a 57th (57D) cable. After the fire was finally extinguished, the field investigation was carried out by internal and external bridge experts. It was found out that, as shown in Figure 3, 21 strands out of 37 strands were broken for the 56D cable and 5 strand out of 44 strands were severed for the 57D cable. Because of severe damage, the Bridge was immediately closed for traffic. The detailed damage assessment and structural analysis were carried out to determine the structural safety of the Bridge. In structural analysis, three cables were assumed to be completely ruptured. The structural analysis using a three-dimensional finite element model showed that the tension force of cables were slightly increased while the compressive/tensile stress of the stiffening girder was substantially increased between the anchorages of the 56D and 57D cables.

Initially the cause of the fire was in question. Because the fire started in the air, the possibility of traffic related fire at deck level such as the Mezcala Bridge, Mexico, in 2007 (Gross et al, 2011) was ruled out. Because the maintenance office staff witnessed the lightning near the bridge before the fire, the lightning was initially presumed to have caused the fire. The cable fire due to lightning strike was reported only once. In 2005, the Rion-Antirion Bridge in Greece experienced the lightning-caused fire on one of upper stay cables and two stay cables had to be replaced (Papanikolas et al 2009). The fire investigation carried out by fire departments and Korean National Forensic Service later confirmed that lightning stuck the cable and caused fire.

The Bridge was closed for 15 days to carry out recovery work. The recovery work process was prepared by carefully studying structural safety of the Bridge at the damaged state and

![Figure 3. Damaged stay cables.](image)
placement of heavy crawler cranes. A number of heavy crawler cranes including 400tonf (3922kN), 200tonf (1961kN) and 100tonf (980kN) were mobilized to remove and replace three fully and partially damaged stay cables. The heavy cranes affected tension force level of the stay cables and compressive stress of the stiffening girder so that the locations of crawler cranes were carefully determined after a detailed structural analysis.

The structural analysis showed that the ruptured 72D cable needed to be first re-erected. After the erection of the 72D cable, remaining strands of the 57D cable were de-tensioned and removed. After the erection of the 57D cable, the similar removal and erection process was applied to the 56D cable.

4 MONITORED CHANGES IN STRUCTURAL SYSTEM

The changes in structural systems during the recovery work were closely monitored by the SSHMS. Initial results from the SSHMS and structural analysis showed that the bridge structure was not seriously damaged. But the cable tensions near the damaged cables and geometry were changed due to the stay cable ruptures.

4.1 Change in cable tension during the fire

The cable tension is estimated using natural frequencies of the cables from accelerometers. As stated earlier, a number of accelerometers were installed on the stay cables to measure the
variation of stay cable force. Figure 4 shows the damaged cables (cables in sky blue color) and the cables with accelerometers (cables with red dot). The tension changes of the cables in the side span, 56th (56D) cable and 69th (69D) cable, and the ones in the center main span, 37th (37D) cable and 39th (39D) cable, were closely monitored and analyzed. The four cables in the upstream cable plane, 37U, 39U, 56U, and 69U, were also equipped with the accelerometers and monitored.

Figure 5 shows cable tensions at the time of the fire. As stated earlier, the fire started at around 6PM and lasted couple of hours. The tension force of the 37D cable in the main span, which is opposite of the ruptured 72D cable in the side span, was reduced while the other cables in the main span were slightly affected. The 69D and 69U cables, close to the 72D cable, were mostly affected as shown in Figure 5. Though tension forces increased in some of the stay cables, the forces were well below the allowable tension limit of $0.45 f_{pu} (f_{pu}$: tensile strength of the strands).

4.2 Changes in geometry

Six GNSS sensors were installed to measure displacements of the stiffening girder and the main pylons. As shown in Figure 2, 2 GNSS receivers were placed on top of the pylons and 4 GNSS receivers were placed on the stiffening girder. The movements of the stiffening girder and pylons were monitored during the fire and recovery work. Though some erroneous data were excluded, the measured data showed changes in geometry during and after the fire.

The longitudinal movements at pylon tops are shown in Figure 6. It shows that both pylons deflected in a longitudinal direction (the bridge-axis direction) when the cables were damaged. During the fire on Dec. 3, 2015, both pylons tilted towards the mid-span because of huge traffic jam. When the fire was finally extinguished and vehicles were cleared, the top of the PY1 pylon almost returned to its undeformed state. However, the top of the PY2 pylon with damaged cables longitudinally deflected about 100mm. The longitudinal deflection of the PY2 top was substantially reduced after the erection of the 72D cable on Dec. 15, 2015, and became almost

![Figure 6. Deflection of pylon tops in the bridge-axis direction.](image)
zero when all three cables are re-erected.

Figure 7 shows that the geometry of the stiffening girder was also affected by cable damages. During the fire, the center of the main span had a downward deflection while those of side spans had an upward deflection (positive upward and negative downward). The deflected shape of the stiffening girder corresponds to the deflected shape of pylons. After the erection of the 72D cable, the deflection of the main girder was also substantially reduced.

5 CONCLUSION

The three stay cables of the 990-m long cable-stayed bridge fully or partially broken due to unusual lighting caused fire. The damaged stay cables were replaced within 15 days. During the fire and recovery work, changes in cable tension forces and geometry was closely monitored by structural health monitoring system (SHMS) to guarantee structural safety of the cable-stayed bridge. Due to damaged cables, tension forces of stay cables were increased or decreased within allowable tension forces. Pylons and the stiffening girder were also deflected. As the cables were removed and reinstalled, the SHMS showed that tension forces of the cables and deflection of the stiffening girder and pylons restored to its level prior to the fire.

References
