THE ENHANCEMENT OF STRUCTURAL INTEGRITY TEST FOR PWR CONTAINMENT BUILDING

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ABSTRACT

Several implementations are provided to enhance the Structural Integrity Test (SIT) for Pressurized Water Reactor (PWR) containment building. A few abnormal measurement results revealed in former SIT performed on Shin-Kori unit 1 led us to prepare SIT thoroughly for Shin-Kori unit 2 and introduce several improvements for the test. The improvements include the pre-performance test, short-distance measurement system for equipment hatch, and new measurement system such as laser system and digimatic indicator also known as dial gauge. With these improvements, more accurate measurement results were obtained successfully from the Shin-Kori unit 2 SIT than the previous test of the other units. In order to achieve the consistency and maintain the robustness of process and test results in SIT, test procedures with improvements are settled in a form of manual.

INTRODUCTION

As reported in the Fukushima nuclear accident, Containment building played a critical role in containing the radioactive materials under Design Basis Accident (DBA) or Severe Accident as final barrier. The structural integrity of the containment building is a crucial factor in satisfying this critical role. SIT, specified by ASME [1] and KEPIC [2], is conducted to demonstrate the structural response of the containment building within predicted limits with any structural damage, and to verify that the structure behave elastically and integrity of steel liner is ensured under test pressure. The Shin-Kori SIT pressure, Psit, is 65.6 psig which is 1.15 times of design pressure Pd. Pressurization is made in five equal steps of increments. For more information on SIT procedure and specification with OPR 1000 which is the 1000MWe PWR in Korea, see Moon *et al*. [3].

SIT for Shin-Kori Unit 1 conducted in 2009 revealed several problems such as the response delay of extensometers at the early stage of pressurization and depressurization, and poor recovery rate of extensometers. In addition, some extensometers failed to measure the displacement in the surrounding area of equipment hatch expected very small displacements. Several attempts were made to improve SIT for Shin-Kori Unit 2 in this study. The pre-performance test was conducted to estimate the reliability of extensometer. Also, short-distance measurement method by installing a temporary structure was suggested to measure the radial displacements in the vicinity of the equipment hatch. The applicability and feasibility of the new measurements systems are evaluated through comparing with the results of the extensometer.

Description of the containment structures is reviewed and numerical modeling for predicting structural behavior is explained in chapter 2. The SIT improvements are presented in chapter 3 and the test results are evaluated in chapter 4.

DESCRIPTION OF CONTAINMENT STRUCTURE AND NUMERICAL MODELING

The containment building of Shin-Kori unit 2 is composed of a prestressed concrete cylindrical wall, a hemispherical dome, and a circular reinforced concrete base mat with steel liner. The height and the diameter of the containment configured in Fig. 1 are 63m and 46m, respectively. Post-tensioned system with unbounded tendons is employed to strengthen the cylindrical wall and hemispherical dome in hoop and meridional directions. The horizontal tendons encircling the containment building are anchored at the buttresses. Three buttresses spaced at 120 degrees are employed.

A three-dimensional finite element simulation has been conducted to predict the structural behavior during pressurization and depressurization. Several schemes in FE modeling are implemented to obtain a better displacement prediction. The containment has been modeled by the commercial finite element program ABAQUS instead of SAP2000 used in the former SIT. ABAQUS is used by a wide range of industries including aircraft manufactures, automobile companies and microelectronics industries, as well as research laboratories and universities. To avoid distorted element which reduces the accuracy of the numerical solution, more refined mesh than that of FE model in Shin-Kori unit 1 is used, and the Concrete wall including buttresses and dome, and base mat have been numerically modeled by 20-node 3-D solid elements instead of tetrahedral elements used in the unit 1 FE model. The inner steel liner has been modeled by 3-node membrane elements and constrained with the inner surface of concrete wall. The reinforcing bars and tendons have been modeled by 2-node truss elements embedded in the walls. The translational movements of the bottom of the base mat are restrained. The soil foundation has been modeled by the nonlinear soil spring element with tension-free to avoid the numerical lift in the bottom of the base mat and slab. The three-dimensional finite element model is shown in Fig.2.

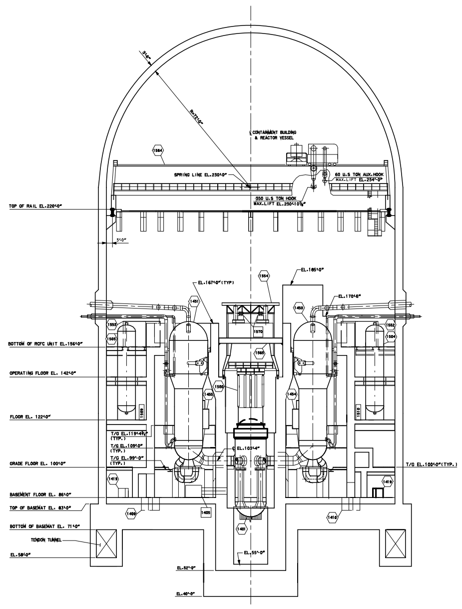
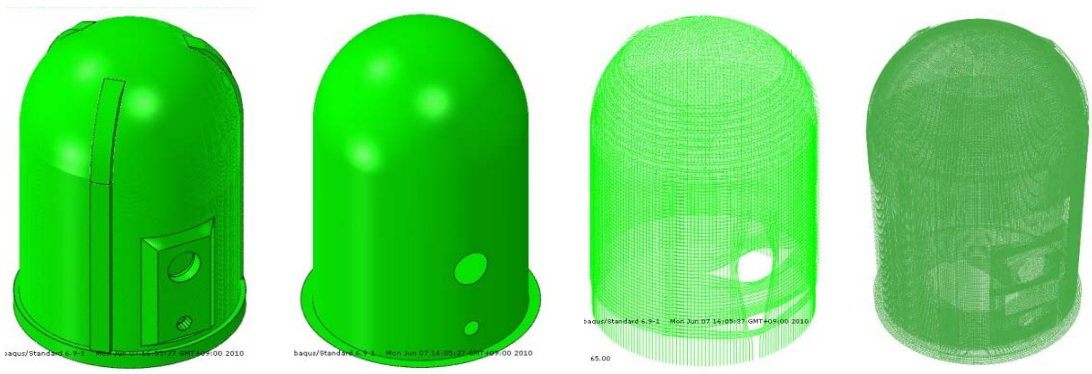


Fig.1: Schematic drawing of Shin-Kori unit 2 confinement building



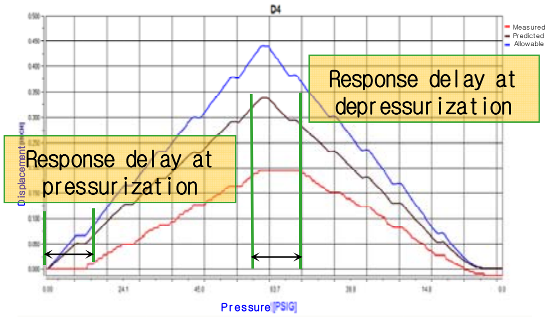
(a) concrete wall and dome (b) inner steel plate (c) tendon (d) reinforcing bar

Fig. 2: Finite Element model for the containment structure.

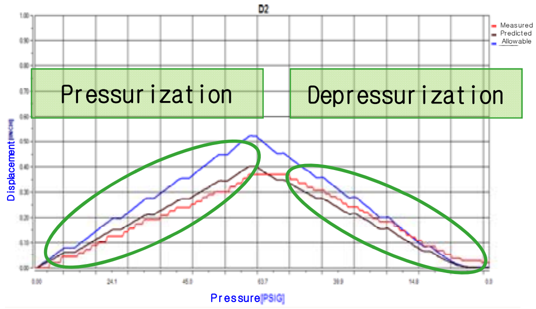
LEARNED FROM THE PREVIOUS SIT AND IMPROVEMENTS

SIT for the containment structure of Shin-Kori unit 1 conducted in 2009 had ceased twice and resumed due to the response delay of extensometer at the early stage of pressurization and depressurization, and poor recovery rate. In addition, some extensometers failed to measure the displacement in the surrounding area of equipment hatch where very small displacement occurred. Examples of these abnormal measurements are shown in Fig. 3(a)-(c).

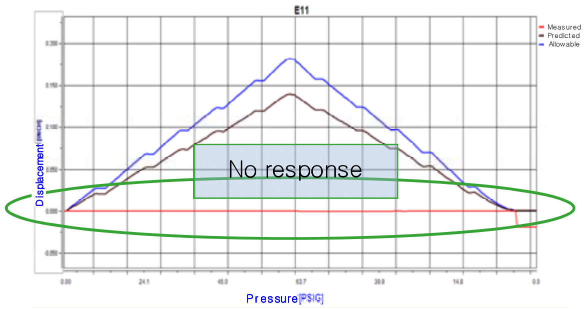
The cut open test of extensometer was carried out right after Shin-Kori unit 1 SIT. Extensometer is a device used to measure changes in the length of an object with invar wire. As shown in Fig. 3(d), about one-third of its cover was cut open to investigate the motion of the inner components as tightening invar wire. The investigation resulted in following improvements of extensometer: the stiffness of sensing bar, at first, is increased by altering the diameter of the bar from 4.85mm to 6.0mm, secondly the inner hole of the front guide bushing narrows from 7.6mm to 7.5mm to assist in maintaining straightness of invar wire, and the inner hole diameter of end guide bushing is adjusted to minimize the friction between the end busing and the invar wire (refer to Fig. 4).



(a) Response delay at the start of pressurization and depressurization



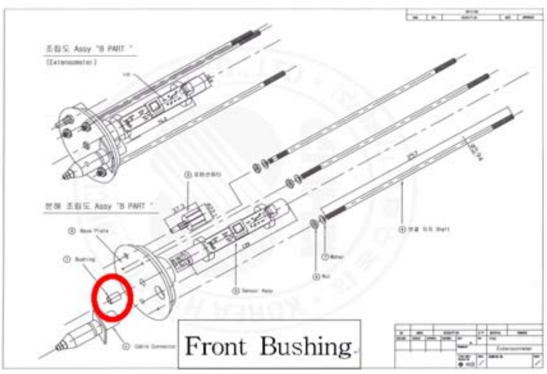
(b) Stepwise response



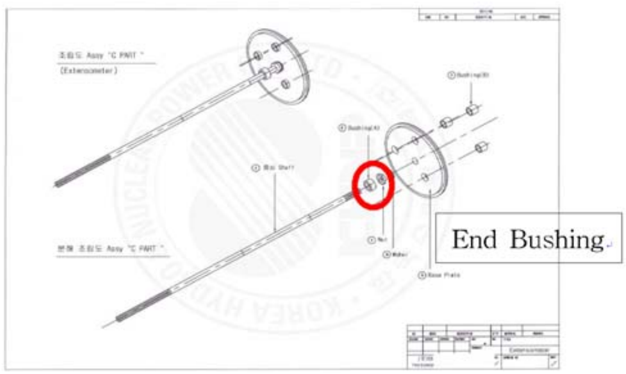
(c) No response at the vicinity of equipment hatch

(d) A cut open test of extensometer

Fig. 3: The abnormal measurement examples in SIT for Shin-Kori Unit 1 and the cut open test of extensometer



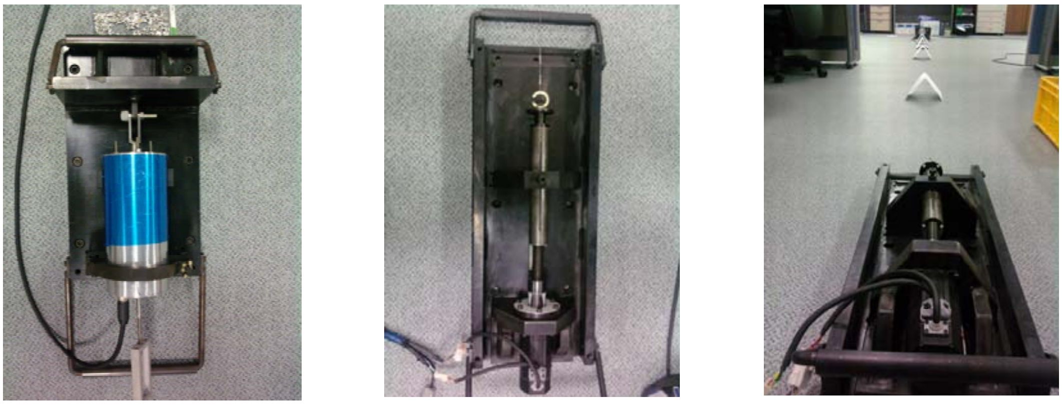
(a) Front guide bushing



(b) End guide busing

Fig. 4: The schematic drawing of the inner components in extensometer

Since SIT is one of the most critical processes in the entire construction schedule, the completion of the test without a failure is extremely important in construction stage. This paper pesents various schemes to arrange SIT for Shin-Kori unit 2 effectively. Pre-performance test has been planned to evaluate the reliability and precision of extensometer enhanced from the cut open test. As the displacement generator shown in Fig 5 pulls the invar wire up to the prescribed displacement, the acquisition system records the displacement by using extensometer, and then the measured displacements are compared to the prescribed displacements. In addition, more than 24-hour measurement is provided to examine whether the extensometer does reasonably express the length variation of invar wire according to the atmospheric temperature change. Fig. 6 shows the invar wire beginning to contract after 2am until 12pm and expand after 12pm. This phenomenon explains that the enhanced extensometer does immediately and accurately express the variation of invar wire by means of temperature change and then show the enhanced extensometer has the sufficient reliability and precision to be applied for SIT.



(a) Extensometer (b) Displacement generator (c) The scene of the test

Fig. 5: The Pre-performance test for measurement system

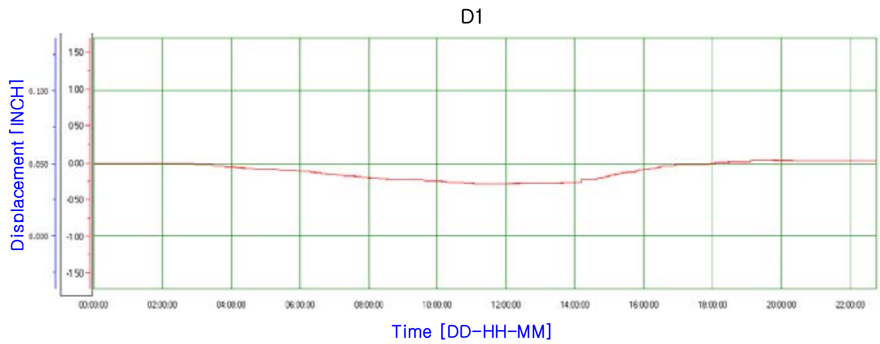
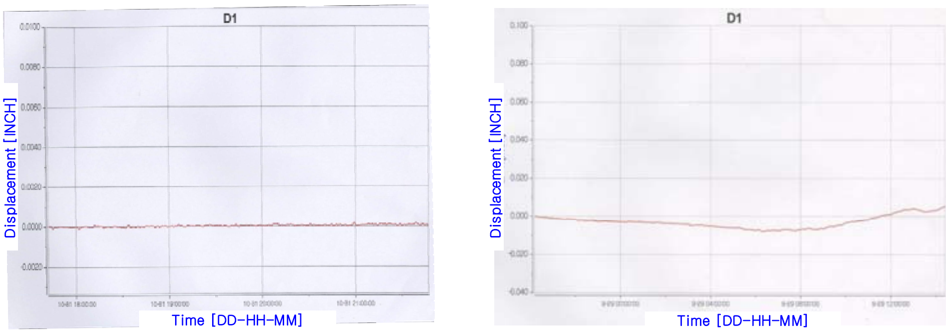


Fig. 6: The 24-hour measurement to evaluate the reliability of extensometer

The initial observation carried out to verify that all measurement system including all measurement sensors, data acquisition and computing systems operates normally for 24 hours prior to the first pressurization. The measured displacement are depicted in Fig. 7, which shows that while the results for the unit 1 fail to describe the behavior of the containment building in accordance with the variation of atmospheric temperature, the displacements for the unit 2 reasonably trace the structural behavior according to the temperature variation. Fig. 7(b) identically represents that the structure contracts when cooled at night-time and expands when heated at daytime. These results indicate the measurement system established also has the sufficient reliability and precision to start pressurization. It is important to note that because the invar wire becomes tightened as the structure expands, the first pressurization is intended to be initiated in daytime when the structure expands in order to reduce the response delay time caused by the deflection of invar wire.



(a) For Shin-Kori unit 1 (b) For Shin-Kori unit 2

Fig. 7: The measured displacement from initial condition test

The displacements of the components surrounding equipment hatch under pressure are very small owing to the thicker concrete wall encircled to the hatch penetration. So it is difficult to obtain valid results, and we fail to detect the meaningful signals in the former SIT for Shin-Kori unit 1. In order to enhance the measurement system for the vicinity of the equipment hatch, the new measurement system such as laser sensor and digimatic indicator are implemented as shown in Fig. 8 and the applicability of these systems are evaluated by comparing with the results of extensometer.

(a) Extensometer (b) Digimatic indicator (c) Laser sensor

Fig. 8: Measurement systems used in SIT.

The upper and lower vicinity of the equipment hatch are selected to apply the new measurement systems. Since the laser sensor and digimatic indicator demand that the measurement sensors should be close to the measured objects, the temporary structure was installed to support the measurement systems in front of the equipment hatch as shown in Fig. 9(b)~(c). Note that careful preparation and communication with other agencies concerned are required to arrange the huge temporary structure into the containment.

(a) Temporary structure (b) installment of the structure (c) three measurement sensors attached

Fig. 9: Installment of temporary structure in front of the equipment hatch

Another purpose of setting up the temporary structure is to minimize the influence of the deflection of invar wire for measuring the radial displacements in the left and right vicinity of equipment hatch. Installment of the temporary structure shortens the length of invar wire by 15m~16.5m from the original length of 18m as shown in Fig. 10.

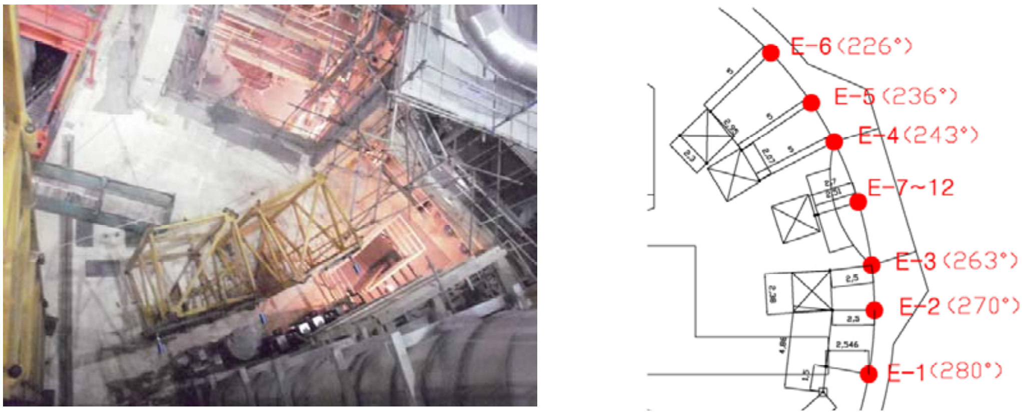


Fig. 10: Installment of temporary structure for the measurement at the left and right area of equipment hatch

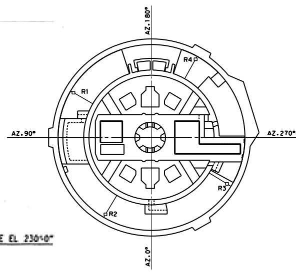
TEST EVALUATION

A total of sixty-six points for displacement measurement are selected in accordance with ASME [1] and KEPIC [2] and consist of 52 points for extensometer, 6 points for digimatic indicator, and 8 points for laser measurement system. Fig. 11 shows the typical Measuring device arrangement. Four temperature sensors are placed to measure the internal temperature and the other three sensors are set up to measure the atmosphere temperature. The internal pressure of containment building is determined by the average of three pressure gauges.

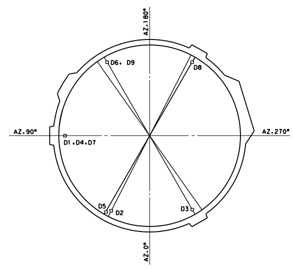
The measured displacements are compared with the predicted displacement obtained by finite element analysis and the allowable displacement specified by ASME [1] in Fig. 12. The measured values are below the allowable displacement and the each residual displacement is less than 10% of the corresponding maximum predicted displacement. These indicate that the containment is bound by the range of elastic behavior. Note that the measured data do not exhibit the stepwise behavior observed in the former SIT, but the data behave linearly.

Although the measured values are close to or even exceed the allowable displacement in the case of V9 in vertical direction, it is possible to judge that the containment structure is within the elastic behavior range because the residual displacements are less than 10 % of the predicted displacement. As shown in Fig. 12(d), the radial displacements measured at the equipment hatch are similar to the predicted displacement and are less than the allowable displacement. These results indicate that the short-distance measurement through installing temporary structure is effective.

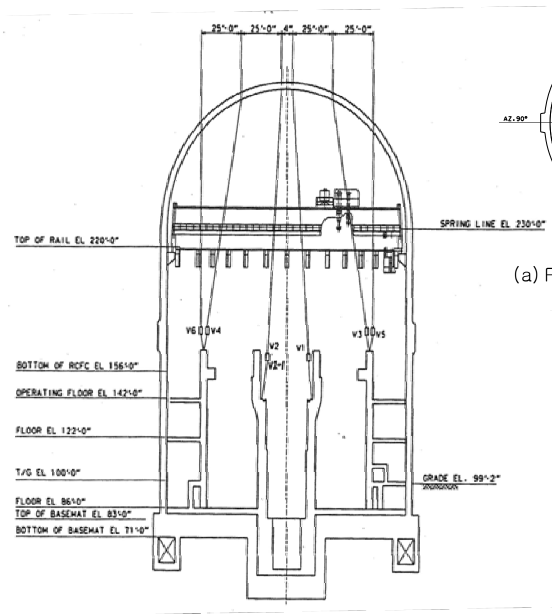
In Fig. 13, the measured data from extensometer, digimatic indicator, and laser sensor are compared with one other and to the allowable displacement. Fig. 13 shows that while the values from laser system are not similar to the results of extensometer, displacements from digimatic indicator are almost identical to the data from extensometer. These results not only show that digimatic indicator might be a feasible substitute for extensometer, but also indicate that the improved results from extensometer using the short-distance measurement are reliable. One the other hand, there are several drawbacks in two new measurement systems. In the case of laser system, the measurements increased as the pressure increased, then diverge from the results of extensometer, i.e., laser system is very sensitive to the pressure. The laser system will be excluded in the next SITs unless the reason for the sensitivity of laser system to the pressure is determined and corrected. Although digimatic indicator is more applicable than laser system, the movement of indicator is easily affected by the dust in the air.



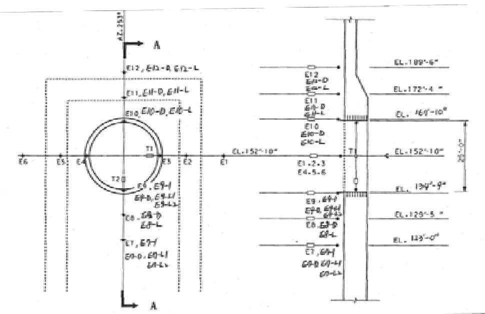
(a) Radial displacement(radius)



(b) Radial displacement(diameter)

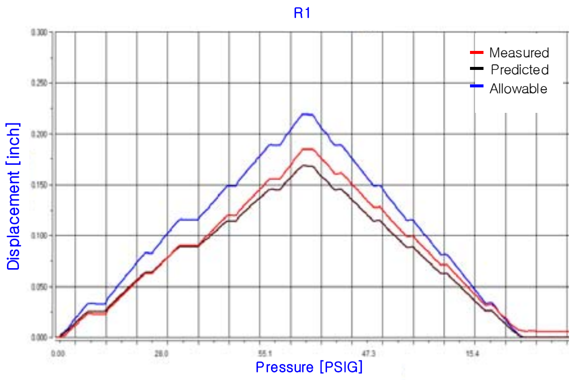


(c) vertical displacement

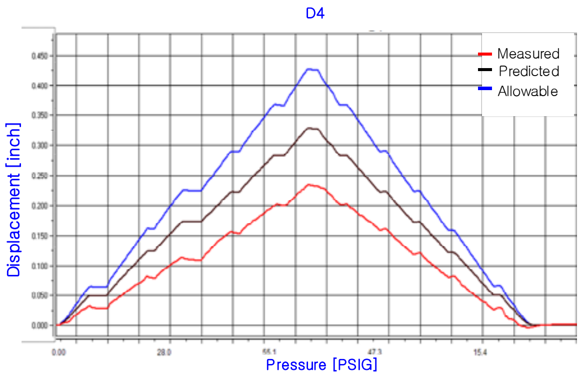


(d) Radial displacement at equipment hatch

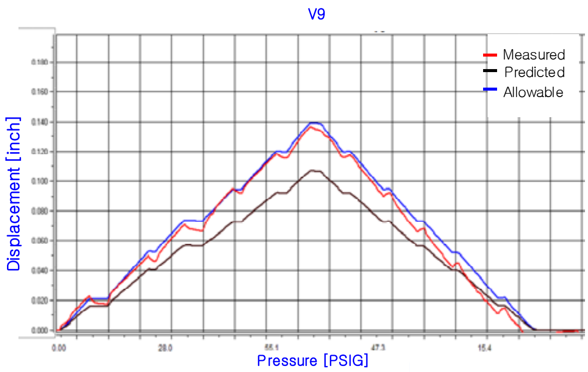
Fig. 11: Measurement arrangement



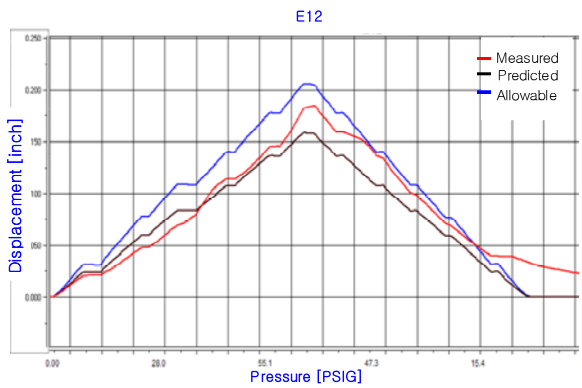
(a) radial displacement (Radius)



(b) radial displacement (Diameter)



(c) Vertical displacement



(d) radial displacement at the equipment hatch

Fig. 12: Comparison of the measured displacement with the predicted and allowable displacements

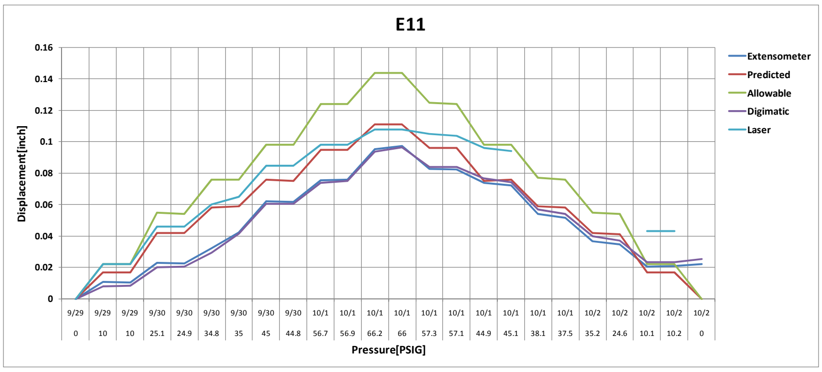


Fig. 13: Comparison of the measured displacement from the extensometer, digimatic indicator, and laser sensor with the predicted and allowable displacements.

CONCLUSION

Several implementations including the component improvements of extensometer, the short-distance measurement for the vicinity of equipment hatch, application of laser sensor and digimatic indicator, and reliability evaluation by pre-performance test and the initial observation are provided to upgrade the SIT for containment structure of the Shin-Kori Unit 2. Measurement results indicate that the containment building is in the range of elastic behavior and satisfy the code criteria for structural integrity. Secondly, the implementations make it easier for Shin-Kori Unit 2 to pass the SIT without a single failure and to obtain more accurate results opposed to the results of Unit 1. Third, the displacements at the equipment hatch where very small displacement occurs are measured by shortening the length of invar wire. Fourth, although there are obvious limitations in long-distance measurement such as radial displacement, it is shown that digimatic indicator is competitive alternative for measuring displacement at the equipment hatch. Last, in order to achieve a high degree of consistency in the test process and the test results, SIT procedures with improvements are established in a form of manual.

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