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Failure behavior characteristics of box culvert using 3-Axes loading system

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ABSTRACT: This paper is to investigate the fracture behavior characteristics of box culvert and incremental crack width of upper slab for the applied loading by the 3-axis loading system. In the 3-axes loading system, loading directions are upper side, left and right side which simulate static traffic load and earth pressure, respectively. With the applied load, crack patterns are investigated on the upper slab, left and right wall. Especially, on the upper slab, crack width is measured by crack gage. Based on the experimental results, structural internal force indices of box culvert are estimated quantitatively.

1 INTRODUCTION

Various factors including vehicle movement, adjacent structure construction, and sinking foundation ground increase the external stress on the top and bottom as well as on the sides of underground structures such as electric cable culverts and tunnels, causing them to undergo structural deformation. Such deformation not only produces structural damages like cracks within underground structures which reduce structural durability, but also significantly impacts the related facilities housed inside the underground structures. (e.g. Yokoyama et al. 1997, Honda et al. 1999, Kwon et al. 2008)

Additionally, in the case of box culvert which is a reinforced concrete structure, the micro cracks contained in the material at the initial stage of concrete curing are expanded in numbers as the external load increases, and the cracks arising from these provide channels of penetration for moisture which lead to corrosion of the reinforcement rods and cause fatal damage to the structure. Increase of such damage leads to rapid deterioration of the structural rigidity and reduces the life of the structure. (e.g. Choo et al. 2008) Therefore, the occurrence and the degree of progress of cracks following increase in external load are recognized as very important factors not only in determining the degree of damage suffered by a structure and predicting its current rigidity but also in planning measures to prolong the life and strengthen the reinforcement of the structure.

The aim of this study is to develop a quantitative evaluation method to determine the current degree of damage and the reduction of structure's rigidity that is applicable to the underground structure of reinforced concrete box culvert. To do so, this paper implemented ultimate failure tests of box culverts under 3-axes loading state. Based on the test results, determined the failure behavior characteristics of the box culvert and measured the crack width changes following increasing loads. Through this process, the degree of structural damage resulting from increase in crack width was experimentally quantified and from this, the structural internal force reduction index($D(\omega)$) of the box culvert was experimentally estimated.

In order to simulate realistic external load conditions, loads were applied using a 3-axes loading system that could simultaneously apply loads to the top and the left and right sides. The formation of cracks on the top slab and the left and right walls following load increases were observed, and the increases in the crack width on the top slab were quantitatively measured. Based on these measurements, the relationship between the behavior and the top slab crack width of the box culvert until the point of ultimate failure was observed and analyzed.

2 EXPEIMENTAL PROGRAM

2.1 *Materials properties*

Ordinary Portland Cement (OPC or type 1) was used to manufacture the test specimen. The 28 days compressive strength of concrete targeted for the mixture was fixed at 24Mpa, which is the standard strength for a box culvert in Korea standard code for concrete. A total of 9 compression specimens were manufactured along with the concrete pouring to measure the strength on the 7th and the 28th day of concrete age, as well as on the day of the test, and water curing was implemented 3 days after the concrete pouring. The compressive strength of the concrete at age 28 days was found to be 26Mpa, surpassing the targeted mixture strength. For reinforcements, D13 mild steel with yield strength of 400Mpa was used.

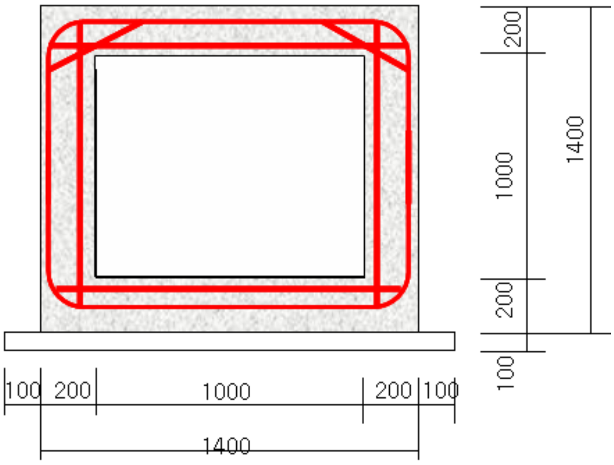

Figure 1. Geometry of Specimen.

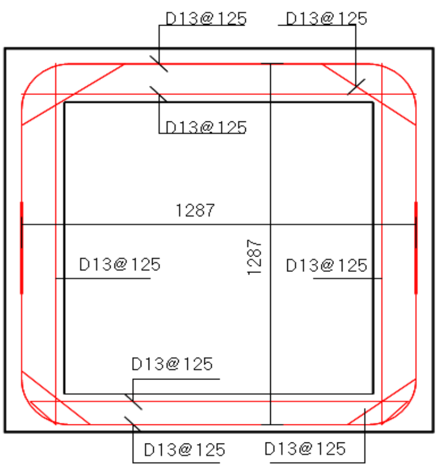

Figure 2. Used reinforcement type and positions.

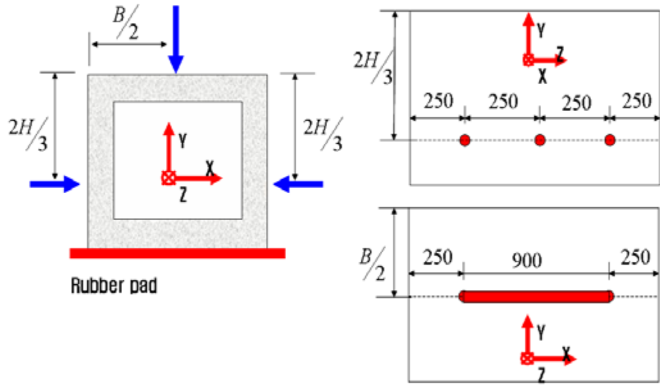

Figure 3. Applied loading direction and.

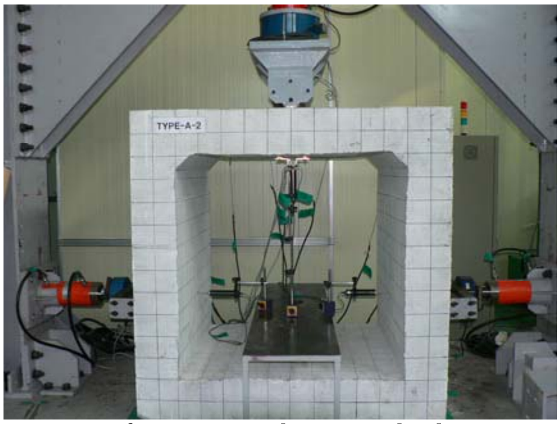

Photo 1. Set up of specimen in the 3-axies loading system.

Photo 2. Closed view of Crack gauge and LVDTs.

2.2 *Specimen shape and size*

The specimens were manufactured based on the standard cross section of the representative square-shaped culvert (box culvert) in actual use but at 1/2 scale of the standard size. A total of 3 specimens were produced and the specifications were set at 1400mm in width, 1400mm in height, and 1000mm in length, and the inner rise and span were set at 1000mm as shown in Figure 1. The walls and the top and bottom slabs were designed to have thickness of 200mm. D13 reinforcements were placed evenly at space of 125 mm in the top and bottom slabs and the walls as shown in Figure 2.

2.3 *Load positions and support conditions*

In order to simulate the actual earth stress on the sides and the stress on the top part, a 3-axes loading system was used to apply the loads as shown in Figure 3, Photo 1, 2. By applying monotonic loading on the top, load increase resulting from the possibility of increase in wheel load and top load was simulated, and a constant load (about 33% of the maximum expecting load) was applied to reproduce the earth stress distribution on the sides. In terms of load positions, as shown in Figure 3, a rubber pad was used as support on the bottom to simulate the behavior of the ground below, and the top load was applied at a position 1/2 of the span. In the case of side loads, they were applied at a position 2/3 of the total rise in order to take into account the distribution of side loads resulting from depth. Additionally for side loads, equal loads were applied to the three points at intervals of 250mm in order produce a constant load distribution in the length direction.

2.4 *Measurement positions and types*

As for measuring the strain of the reinforcements, 6 gauges were embedded in each of the top slab and the left and right walls and the strain of the reinforcement in the horizontal and vertical directions were measured. The surface strain of the concrete was measured from a total of three positions. In addition, for measuring the horizontal and vertical displacements of the specimen, two 50mm LVDTs were attached on each of the inside wall of the left and right walls and three were attached to the inside wall of the top slab. Generally in the case of box culvert structures, the longitudinal cracks in the top slab caused by increase of traffic load on top or from impact of vibration often result in direct reduction of structure's rigidity. Therefore, in order to experimentally measure the crack width increase due to the impact of load on top, crack gauges that can measure the horizontal crack width on the top slab were installed in this test, as shown in Photo 2 and Figure 3. To facilitate measuring the crack width within a limited area, a preliminary crack of minimum size (width 2mm, depth 8mm) was made and then the amount of increase in the crack width was measured.

3 EXPEIMENTAL RESULTS

3.1 *Load-displacement relationship*

The vertical load-average vertical displacement relationships for a total of three specimens are illustrated in Figure 4., and the relationship diagram of horizontal displacement of the walls resulting from increase of horizontal load is illustrated in Figure 5.

Test results showed that maximum vertical load value appeared within approximately 243kN~301kN range. In the case of top slab vertical displacement, a vertical upward displacement of about 0.5mm occurred due to the impact of the initial side horizontal loads. The initial crack occurred in the center of the bottom surface of the top slab when the vertical load was around 80~90kN. As the load increased the width of this crack expanded gradually. In Specimens #2 and #3, sudden longitudinal cracks appeared on the top of the left and right walls at 140kN, and as the vertical load increased thereafter, the crack widths expanded. The horizontal displacements of the walls showed displacement error of about 1mm due to the initial horizontal loading, and as the vertical load became greater, the horizontal load value also increased as shown in Figure 6. The horizontal load applied to the left and right walls produced an eccentricity of about 8.5% relative to the right side load.

3.2 *Vertical load-Average CMOD relationship*

The horizontal load-average CMOD relationship of the vertical reinforcement in the walls, which averaged the CMOD values measured by a total of four crack gauges, are illustrated in Figure 7. In all specimens, opening displacements of less than 1mm occurred up to the vertical load of 200kN, but after the failure of the reinforcement rods, the width of the cracks expanded rapidly, indicating that the eccentricity did not impact the test results.

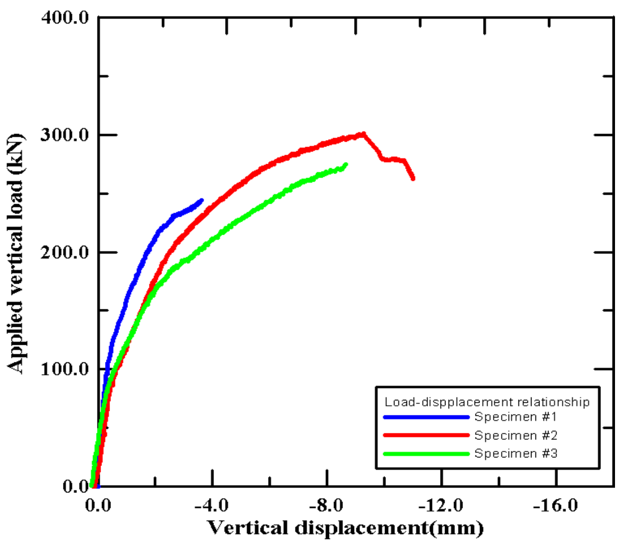

Figure 4. Applied vertical load – average vertical displacement relationships of specimens.

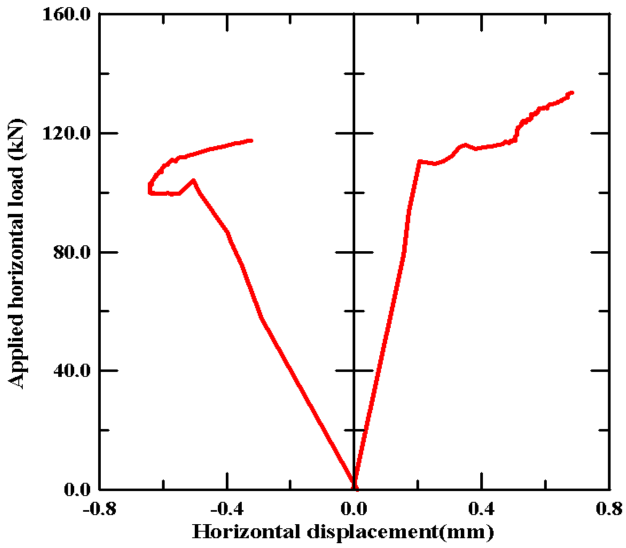

Figure 5. Relationship of horizontal load – displacement.

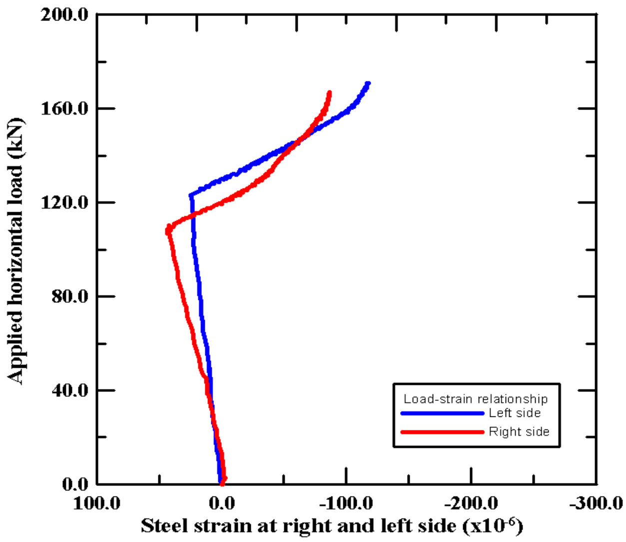

Figure 6. Relationship of applied horizontal load – steel strain of right and left sides.

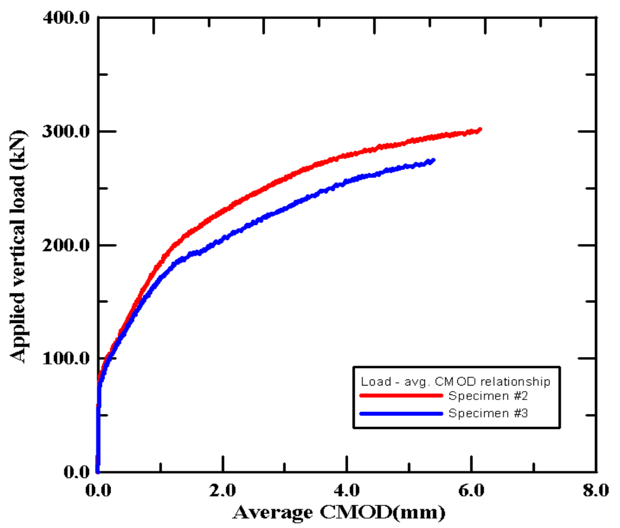

Figure 7. Vertical load-average CMOD relationships of specimen #2 and #3.

3.3 *Crack patterns*

Figure 8 is shown the crack pattern observed in the specimen #2. In all specimens, when the vertical load was about 80kN~90kN, initial cracks were observed in the left and center of the lower part of the middle area of the slab. Afterward, when the load reached 130kN, similar cracks in the direction of the slab length were observed in the center area of the lower part of the slab. At vertical load of 160kN, cracks were observed in the exterior of the left and right walls and the left top part of the center area of the slab. At vertical loads of 210kN and 240kN, cracks located 200mm and 250mm from the top and in the direction of the specimen length occurred in the upper part of the walls at the same time, and the width of these cracks expanded as the vertical load increased. Thereafter, as the vertical load increased, the main cracks in the center of the lower part of the slab progressed further along the length direction and the crack width also expanded further, and cracks in the length direction were observed in the area where the slab and the walls joined. When the vertical load reached around 300kN, the width of cracks expanded rapidly and the arch-shape crack in the lower part of the center area of the slab widened suddenly, leading to the final failure.

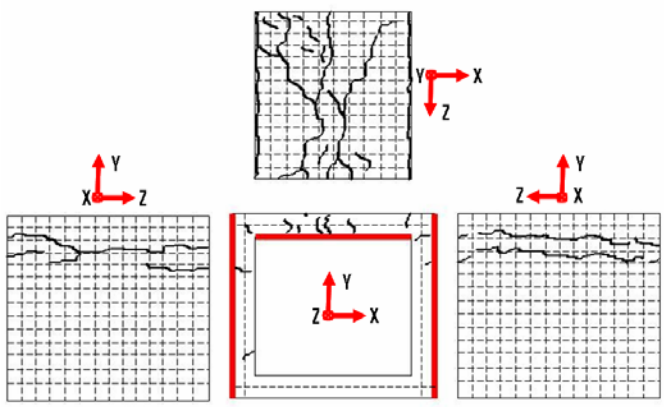

Figure 8. Observed crack pattern of specimen #2.

3.4 *Estimation of structural internal force reduction index based on test results*

In this paper, the structure's internal force reduction (or degree of damage) shown through the model testing was expressed as a function of the width of the crack occurring in the lower part of the top slab; and through this, the structural internal force index of the structure was estimated. To do this, the structural internal force reduction index was defined as equation (1).

$$D(\omega) = 1 - d(\omega) = 1 - \frac{f(\omega)}{f_{\max}} \tag{1}$$

where, $D(\omega)$ = structural internal force reduction index; $d(\omega)$ = damage index; $f(\omega)$ = amount of load increase from crack width increase; f_{max} = maximum load or design load obtained from test; ω = crack width at top slab (mm). If $D(\omega)$ = 1.0, then the internal force at the time of construction is retained, but if $D(\omega)$ = 0.25, then it indicates a 75% internal force reduction compared to a healthy state.

The damage index for Specimens #2 and #3 from the load-average CMOD relationship obtained from the test results is illustrated in Figure 9. Up to the damage index value of 0.3, the longitudinal crack width of the top slab is within about 0.3mm and shows very small increase in crack width. When the longitudinal crack width of the top slab is about 1.2mm, the damage index is around 0.7, but afterwards, CMOD shown to increase at a greater rate compared with the increase in the damage index as shown in Figure 10 and 11.

Therefore, in this paper, the initial internal force damage index when the structural damage begins and the maximum internal force damage index when the structure's internal force completely deteriorates were assumed to be 0.3 and 0.7, respectively, and the corresponding crack widths are determined to be 0.3mm and 1.2mm. Based on these, the internal force index of reinforced concrete box culvert structure is calculated to be the structural internal force index, divided into and selected as 5 sections depending on the longitudinal crack width (mm) of the top slab, as shown in Table 1.

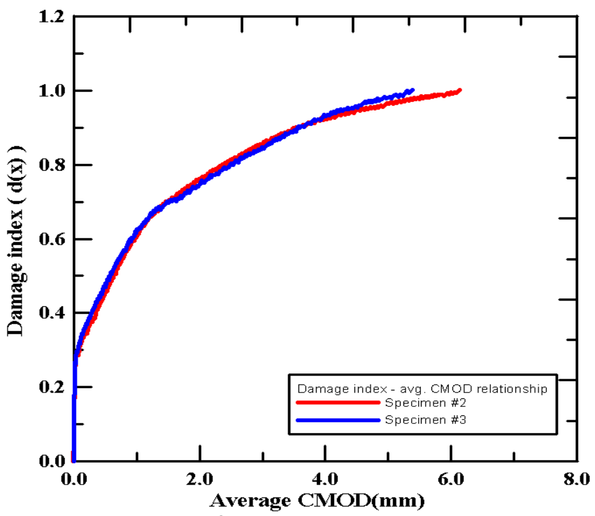

Figure 9. Relationship of damage index and avg. CMOD.

Table 1. Range of structural internal force reduction index and crack width of top slab.

$D(\omega)$	ω
$D > 0.7$	$\omega < 0.3$mm
$0.6 < D \leq 0.7$	0.3mm $\leq \omega <$ 0.8mm
$0.5 < D \leq 0.6$	0.8mm $\leq \omega <$ 1.0mm
$0.3 < D \leq 0.5$	1.0mm $\leq \omega <$ 1.2mm
$D \leq 0.3$	1.2mm $\leq \omega$

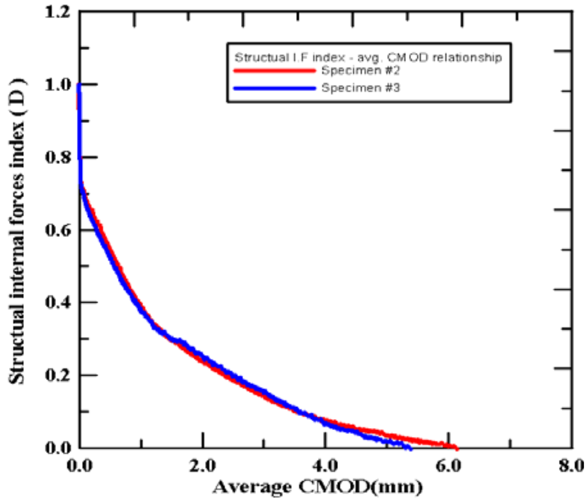

Figure 10. Relationship of structural int. force index and avg. CMOD.

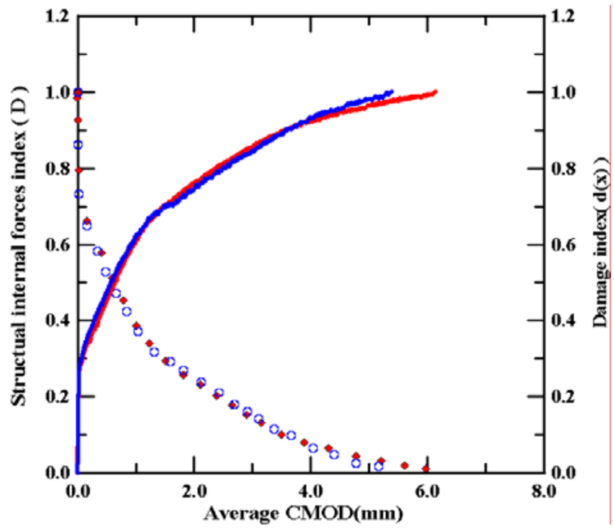

Figure 11. Relationship of structural int. force index, damage index and avg. CMOD.

4 CONCLUSION

This study introduced a structural internal force index for quantitatively evaluating the internal force of box culvert structure, which is needed for the goal of developing a structural evaluation system for underground structures. For this end, failure tests using static 3-axes loading system were done on 3 box culvert model specimens. In order to measure the width of the cracks in the lower part of the top slab caused by vertical load increase, a preliminary crack of 2mm width and 8mm depth was made in the lower part of the top slab and the crack widths were measured with crack gauges.

Based on the test results, the relationship of horizontal crack width change in the top slab to vertical load was obtained, and from this, the degree of structural internal force reduction due to increase in crack width could be determined. In addition, by introducing the concept of structural internal force index to enable prediction of change of internal force relative to crack width, which is needed for structural internal force evaluation, the structural damage index of reinforced concrete structure for the crack width of the top slab was developed and the formula for calculating the structural internal force index was proposed. Based on these, the structural damage level of electric culvert structure was divided into 5 stages and the crack widths of the top slab were proposed for each stage.

For quantitatively evaluating the current internal force state, a damage estimation function applicable in an interpretative method was newly defined for crack width. When current internal force is evaluated by an interpretative method based on this, it is deemed possible to express the degree of internal force reduction of the localized area as well as the whole structure just by using the current crack width and the damage estimation function.

5 ACKNOWLEDGMENT

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