Measurements of Strain Relief in Concrete Cubes with Slot Cutting

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Abstract: An experimental procedure was developed to measure strain relief in plain concrete cubes (305 mm) under a pre-determined compressive load. The cubes were statically loaded and the resulting strains were measured to obtain baseline values of strains. After the baseline strains were measured, slots and holes were made with various depths and spacings. Strain relief was observed as a function of depth and spacing between the slots and holes. From the comparison of the physical test results with linear-elastic numerical models, it was found that the amount of strain relief by making slots in cube tests is related to the slot depth-to-spacing (SDS) ratio. The compressive strains between two slots decrease with increasing SDS ratio and reach to zero strain at the SDS ratio of 0.35. At SDS ratio higher than 0.35, the strains between two slots become tensile. Some insights were presented to improve the experimental procedure.

Key words: Prestress concrete; strain relief; residual stress; load carrying capacity.

INTRODUCTION

Determining residual prestress in pre-tensioned or post-tensioned bridge girders is paramount to establishing a Military Load Capacity (MLC) classification. The MLC is the information that military personnel use to determine the safe load limit for transporting convoys across bridges. A research program was developed to help classify a prestress concrete bridge without prior knowledge of the prestressing present in the structure. The basic idea of this research project is to determine strain relief of the prestressed structure by making slots or holes in the structure. From the measured strain relief of the prestressed concrete structure, the amount of strain present in the structure without any live load can be estimated. From this estimation, the serviceability criteria of the structure can be determined.

There were several efforts to determine residual prestress in prestressed concrete members by drilling holes. One effort includes making a hole (75mm or 150mm) and measuring the strains arranged in outer perimeter of the hole. This method turns out to be less effective in low level of prestress, and leads to errors. Kesavan et al. tried to use core trepanning technique to measure strain relief mounted inside the core up to 90%. This technique, however, have limitations to use waterproof strain gauges and have possibilities to damage the strain gauges during the core trepanning.

The objectives of this study were to understand the mechanics of physical cube tests by comparing measured vertical strains with numerical analysis values and to investigate the effects of strain relief by making slots and holes in a concrete cube. With a pre-determined maximum compressive load, plain concrete cubes were loaded gradually and strains between slots and holes were measured. Linear-elastic numerical models simulating the physical tests were developed and the analytical results were compared with measured strain relief values. From this comparison, some insights were obtained to improve the experimental procedure.

Geometry of Cube Specimens and Physical Cube Tests: Seven plain concrete cubes were fabricated using a “SAC-5” concrete mix design with dimensions of 12 inches (305 mm) for each side. The mix proportions of “SAC-5” concrete are provided in Table 1. The specimens were fabricated using the standard mix procedure and were cured in a moisture room until the test began. The average 28-day compressive
strength of the five 6x12" concrete cylinders was 5,266 psi (-36.3MPa). The measured average secant modulus of the concrete at the peak stress was 6.04x10^6 psi (-36.3MPa). The measured average secant modulus of the five 6x12" concrete cylinders was 5,266 psi. 

In order to check the symmetry of the specimen and strain gauge signal, a pre-run test was first performed without any slots or holes in the specimen. Two strain gauges with 2 inch (-50.8 mm) gauge length were mounted on the mid-point of opposite sides of the cube specimen as shown in Figure 1. The cube specimen was placed on a steel plate (12" x 12" or 30.5 cm x 30.5 cm). A rectangular steel plate (12"x12"x1/2"or 30.5 cm x 30.5 cm x 12.7 mm) and a circular steel plate (10" diameter, and 1/2" thickness) were placed on the top surface of the concrete cube. Loads were applied by a circular loading cell with a diameter of 10" (25.4cm). The use of the circular steel plate with a smaller dimension compared to the cube specimen (12", 30.5 cm) may cause uneven stress application, and may develop high tensile strain at the outside surface. With unsymmetrical slot depth in cube specimens, the applied force can be further distorted and misaligned. These issues, along with numerical analysis results, are presented in later section.

A universal testing machine with a maximum capacity of 440 kips (1,957 kN) of compressive load was used. Compressive load was applied on the concrete cube at a rate of 3,500 lb/sec (-15.6 kN/sec) and compressive strains were recorded using a data acquisition system. Once the applied load reached the maximum load of 300 kips (-1334.5 kN), the load was released at the same rate as the loading rate. The maximum load was chosen to develop a compressive stress equal to the 40% compressive strength of concrete cube to prevent any damage in concrete specimen. The measured vertical compressive strain of all the cube specimens were averaged to represent strain in cube specimens without slots and holes, and was used as a baseline strain. The average strain was curve fitted using a 10th order polynomial curve, and is shown in later graphs. The maximum compressive strain of fitted curve was 537 με in cube specimens under 300 kips of compressive loads.

After the pre-run test, the specimen was cut to make slots and/or drill holes according to the test matrix shown in Table 2. Slots of two spacings (63.5mm and 76.2 mm) and four depths (12.7mm, 25.4mm, 38.1mm, 38.1mm, and 50.8mm), respectively were applied to eight opposing faces, two on each cube. Two slots with specified spacings and depths were made on an edge of a concrete cube using a diamond sawing blade (1/4", -6.45mm width), as shown in Figure 2. To maximize the use of all four surfaces of the concrete cube, two slots were sawn with the same spacing but with a different depth on the opposite edge of the cube. Even though this approach uses the specimen efficiently, different depths of slots in opposite side of compressed cube specimen might have caused unsymmetrical loadings and deformations as discussed in a later section. On the other two edges of the cube, two holes were driven using a drill bit with the same spacing as slots. Four different drill bit diameters (6.4mm, 7.9mm, 9.5mm, and 12.7mm) were chosen. The depth of the hole was determined to be 2.5 times the hole diameter based on the ASTM Standard E837-01 for determining residual stresses by the hole-drilling strain-gage method[4]. By having both slots and holes in a specimen loaded in compressive stress, reciprocal effects were added in the measured strains, which would make the produced results more complex.

Using the prepared specimen (Figure 3), compression tests were performed in the same manner as the pre-run test. The applied load and vertical strains were recorded using a data acquisition system for further analysis. Figure 4 shows typical applied loads.
Fig. 1: Compression Test of Concrete Cube Specimen (No Slots and Holes).

Fig. 2: Cutting Slots with a Diamond Blade in Circular Saw.

Fig. 3: Concrete Cube #3 with Slots and Holes.
(Note for unsymmetrical arrange of slot depth, 0.5” on left side and 1.0” on right side).
and strains measured from the testing of cube #3. Compared to the pre-run strain, the measured compressive strains were relieved due to slots and/or holes. As expected, deeper slots and holes in a cube specimen relieved more compressive strains in a cube specimen. The 0.5” slot developed 160 με of compressive strain while the 1.0” slot produced tensile strain (60 με) at the maximum load of 300 kips (1,334.5 kN). The amount of strain relief of 0.5” slot is 70% of the pre-run strain. In the case of drilled holes, 0.5” and 3/8” diameter holes relieved 347 με and 289 με, respectively. It should be noted that cube #3 specimen had both slots and holes in a non-symmetrical manner.

Experimental Results: Using the measured vertical strains in cubes #3 and #4, the amount of strain relieves for different hole diameters and slot depths are compared in Figures 5 and 6. All the curves were fitted using 10th order polynomial curves. The measured strains of cubes #5, #6, and #7 were excluded from the comparison because those cubes had slots only. The measured vertical strains at the maximum load (300 kips) are summarized in Table 2. By comparing measured strains (Figures 5 and 6), it is clear that the measured strains are proportional to the applied compressive loads for different slot depths and hole diameters except in the early stage of the tests and the transition from loading to unloading. The measured strain difference (relief) before and after strain relief using slots or holes can be used to estimate applied stresses in the cube and can further predict remaining prestress in prestressed structures. This observation shows that drilling holes and/or cutting slots and measuring strain relief between the holes and slots is a promising technique to estimate prestress in pretensioned or post tensioned concrete structures.

Figure 5 shows the strain relief of drilled holes with 3” spacing in cubes #3 and #4. The measured compressive strains decrease with increasing drill bit diameter (and also depth of hole since the depth of the hole is 2.5 times of hole diameter). In other words, the strain relief is proportional to the drill diameter and depth, as predicted. The strain relief of slots with 3” spacing in cubes #3 and #4 are presented in Figure 6. In this case, the strain in 0.5” slot depth is only compressive while the other strains are tensile. This shows that strain relief in cube specimen is very sensitive to the slot depth. The maximum strain relieves for different hole diameters and slot depths for 2.5” and 3.0” spacings are shown in Figure 7. This figure clearly shows that the amount of strain relief is much higher for the case of slot cutting. This observation can be explained by considering the extent of strain relief using the holes and slots. The slots have much wider extent of strain relief compared to the holes, and consequently cause higher strain relief. The increases of strain relief with increasing slot depth or hole depth are different for different spacings. This observation is attributed to the fact that both slots and holes are made in a cube specimen, and the strain relief heavily depends on the slot depth in a cube specimen. The reciprocal effects of slots and holes are further discussed in the later section.

Finite Element Models: A three-dimensional finite element model has been developed using a commercially available software ABAQUS to predict strain relief by making two slots on an edge of concrete cube specimen. The model took advantage of symmetry of the cube specimen and modeled only ¼ of the cube to minimize computation time as shown in Figure 8. Three-dimensional solid elements (C3D8, 8-
Fig. 5: Comparison of Drilled Hole Strain Relief with 3” Spacing (Cubes #3 & 4).

Fig. 6: Comparison of Strain Relief for Slot Cut with 3” Spacing at Different Slot Depths (Cubes #3 and 4).
Fig. 7: Strain Relief in Compressed Cube Specimen Due to Holes and Slots.

Fig. 8: ¼-Model of Cube Specimen Without Slots and Holes.
node linear brick) were used with the boundary conditions at the bottom surface and symmetry surfaces. The elastic modulus of cube concrete (6.04 x 10^6 psi, -41.6 GPa) was obtained by measuring secant modulus of concrete cylinder. Poisson’s ratio of the concrete was assumed to be 0.19. A typical value of elastic modulus and Poisson’s ratio was used for the steel plate (E = 29 x 10^6 psi -200 GPa and v = 0.3). A uniform pressure (3,821 psi =-26.3 MPa = maximum elastic modulus and Poisson’s ratio was used for the concrete was assumed to be 0.19. A typical value of

for values outside of the limits do not apply to tick mark contours. The vertical strains on the surface are mostly symmetrical with respect to the vertical middle cross-section. Figures 10 and 11 show ¼-models for 3” spacing slot at a depth of 0.5” and 1.0”, respectively. The fringe patterns of the models show the vertical strains at the outer and inner surfaces of the ¼ model. The range indexes of the vertical strains were intentionally kept the same as the full-size model and ¼ models to be able to easily compare the vertical strains. From this comparison, it was found that the ¼-models and full-size model with slots at different depths on opposite sides predicted vertical strains very closely. However, in cases where the cubes had holes with different diameters and depths on the opposite sides, different results were noted.

Due to the application of vertical force in the circular steel plate of 10” diameter, the force is not uniformly distributed to the top surface of the cube even though there is a steel plate of 12”x12” between the circular plate and concrete cube. Figure 10 clearly shows that the stress inside the concrete cube is quite different from the outside within the top portion of the cube. The differences in the force in the outside and inside of the concrete cube and the slot depth in the opposite sides actually cause non-symmetric behavior of the full-size model. The deformations of the models in Figures 9 through 11 were drawn using a scale factor of 1. The deformation of full-size model in Figure 9 shows distortion and misalignment of rectangular steel plate and circular plate. Therefore, for experimental set-ups, the use of a small circular plate (10”, -25.4 cm diameter) and making different depths

Finite Element Analysis for Concrete Cubes with Slots: The vertical strains of ¼-model of concrete cube were compared with that of full-size model. Figure 9 shows the full-size model for concrete cube #3 with 3” spacing slots at a depth of 0.5” and 1.0”. The fringe pattern of the model presents the vertical strains developed on the surface of the cube. In the figure, the darker areas are in compressive stress and the brighter areas are in tensile stress. The limits of the fringe pattern are set as 100 με in the tensile strain and -600 με in the compressive strain respectively. Gray-scales

<table>
<thead>
<tr>
<th>Cube #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>Slot Spacing (in.)</td>
<td>2.5”</td>
<td>2.5”</td>
<td>3.0”</td>
<td>3.0”</td>
<td>3.0”</td>
<td>4.0”</td>
<td></td>
</tr>
<tr>
<td>Slot Depth (in.)</td>
<td>0.5”</td>
<td>-45 με</td>
<td>-165 με</td>
<td>-200 με</td>
<td>-259 με</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td>1.0”</td>
<td>65 με</td>
<td>71.5 με</td>
<td>-100 με</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1.5”</td>
<td>60 με</td>
<td>65 με</td>
<td>-75 με</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>2.0”</td>
<td>30 με</td>
<td>65 με</td>
<td>40 με</td>
</tr>
<tr>
<td>Hole Spacing (in.)</td>
<td>3.0”</td>
<td>3.0”</td>
<td>3.0”</td>
<td>3.0”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilled Hole Diameter (in.)</td>
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<td>-290 με</td>
<td>-193.5 με</td>
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<td></td>
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<tr>
<td></td>
<td>3/8”</td>
<td>OL</td>
<td>-251 με</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5/16”</td>
<td>-330 με</td>
<td>-407.5 με</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/4”</td>
<td>-350 με</td>
<td>-507 με</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Note:
1. Values are measured peak strain (με) at maximum load (300,000 lb).
2. Positive values are tensile and negative values are compressive strains.
3. The average maximum compressive strain in pre-run test is 537 με.
4. Blank cells in table do not have collected data.
5. OL: suspected outlier
Fig. 9: Vertical Strains in Full-size Model of Cube Specimen with 3.0" Spacing and 0.5" and 1.0" Slots

Fig. 10: Vertical Strains in ¼ Model of Concrete Cube with 3" Spacing and 0.5" Slots.
of slots on the opposite side should be considered. To be able to apply uniform force on the entire concrete cube, a smaller size cube (7”x7”, -17.8 cm x 17.8 cm) is suggested. To prevent non-symmetrical behavior of the cube specimen, the same depths of slots should be made on the opposite side. To maximize the effective use of concrete cube, it is suggested to start with smallest depth of slot. After completing the test, a deeper slot can be made on the same specimen to explore the effects of slot depth.

**Reciprocal Effects of Slots and Holes with Different Sizes:** To measure strain relief of concrete cubes, two slots and two holes were made on all the four surfaces of the concrete cube with different depth and diameter. Table 1 lists all the slot depths and hole diameters for all the four concrete cubes.

To understand the reciprocal effects of slots and holes with different depths and diameters, four different models were developed for cube #3, as shown in Figure 12. Figure 12(a) shows ¼-model with 0.5” depth slot only. The ¼-model with only a 0.5” hole is shown in Figure 12(b). Figure 12(c) represents the ¼-model with 0.5” depth of slot and 0.5” diameter of hole. Figure 12(d) shows a three-dimensional model with 0.5” and 1.0” depth of slots and 0.5” and 3/8” diameter of holes. After analyzing four different models using the 300 kips (-1,334.5 kN) static load, the average values of the vertical strains of the elements within the 2-inch gauge length between slots and holes were obtained (shown in Table 2). From Table 3, it is clear that ¼-models with only slots or holes do not predict the real test results of cube represented by full-size model. The ¼-model with slots and holes, however, results in similar vertical strains between the slots in the full-size model. These results justify using ¼-model with slots and holes to predict vertical strains of concrete cube test. On the other hand, the vertical strains between the two holes are not the same for ¼-model and full-size model. This is related to the large effects of slots on the other edge. Since the slots are made through the edge of the cube, the strain effects are significant. On the other hand, the holes are made with the given diameter of the holes and thus the effects of strain relief are small. For future experimental program, the slot cutting appears promising to measure strain relief while making small hole is not recommended.

**Comparison of Measured Strains with Numerical Analysis Results:** Vertical strains in 2” gauge length between the two slots were calculated using ¼-model with slots and holes, and were compared with the actual measured strains in concrete cubes using the 300 kips (-1,334.5 kN) static load. Figure 13 shows vertical strains for different slot spacings and depths. Using 2nd order polynomial curves, the calculated vertical strains represent the measured vertical strains.
Table 3: Reciprocal Effects of Slots and Holes on the Measured Strains in Cube #3

<table>
<thead>
<tr>
<th>Models</th>
<th>Strains Between Slots</th>
<th>Strains Between Holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>¼-Model (a)</td>
<td>-286 με</td>
<td>N/A</td>
</tr>
<tr>
<td>(b) Hole only</td>
<td>N/A</td>
<td>-464 με</td>
</tr>
<tr>
<td>(c) Both Slots and Holes</td>
<td>-313 με</td>
<td>-439 με</td>
</tr>
<tr>
<td>Full-Size Model (d) Both Slots and Holes</td>
<td>-317 με</td>
<td>-358 με</td>
</tr>
</tbody>
</table>

Note:
Two opposite sides of cube #3 have two slots with 3” spacing. One side has ½” depth slots and the other side has 1” depth slots. The two opposite sides of cube #3 have two holes with 3” spacing. One side has ½” diameter holes and the other side has 3/8” diameter holes.

Fig. 12: Four Different Models Comparing the Reciprocal Effects of Slots and Holes.

To understand the effects of slot spacing and depth on the strain relief, an ideal ¼- model has been generated by changing loading configuration and cutting geometry. The ideal model has a uniform pressure (2,083.3 psi) applied on the top surface of the rectangular steel (12” x12”, -30.5 cm x 30.5 cm) plate without circular plate. Edge slots are assumed to be made in a symmetrical manner so that the same depth of slots is made on opposite side of the cube. Figure 14 shows the configuration of the ideal ¼-model. The elements between the two slots were meshed with 0.5” length square so that size effects are minimal at the 2” spacing of gauge length. The calculated vertical strains in 2” gauge length between two slots with different spacings and depths are shown in Figure 15. As shown in this figure, the strain relief, by making slots in concrete cube, is related to the slot depth-to-spacing (SDS) ratio. The compressive vertical strains between the two slots decrease with increasing SDS ratio and reach to zero strain at the SDS ratio of 0.35.
Fig. 13: Comparison of Measured Vertical Strains with Values from Numerical Analysis for Different Slot Depths and Spacings.

Fig. 14: Ideal ¼-Model with Uniform Pressure and Symmetric Geometry (0.5" Depth Slots, No Holes).
SDS ratio higher than 0.35, the strains between the two slots become tensile. In future experimental studies, it is suggested to limit the SDS ratio to less than 0.35 since the strain relief within the compressive regime is only interest.

Summary and Conclusions: Developing an analogous method to the ASTM residual stress determination procedure for steel was the motivation of this study. An experimental program was developed to measure strain relief between two slots or holes on the surface of plain concrete cubes under a defined static load. Before any stress relieving slots or holes were applied, the concrete cube specimens were statically loaded and the resulting strains were measured to obtain baseline values of strains. After the baseline strains were measured, slots of two spacings and four depths were applied to the eight opposing faces, two on each cube. Additionally, holes around strain gauges on other side of the concrete cube specimen were drilled using the same spacing and four different drill bit diameters. Strain relief was observed as a function of the depth and spacing between the slots and holes. The test results show that the measured strains are proportional to the applied compressive loads for different slot depths and hole diameters except in the early state of the tests and the transition from loading to unloading. As predicted, deeper slots and holes relieved more compressive strains in a cube specimen.

Linear-elastic numerical models were developed to simulate the physical tests of concrete cubes, and to compare calculated strain relief values with the corresponding measured values. There is a good agreement between the measured vertical strains and the calculated strains, but some issues were raised during the experimental procedure. These included non-symmetric condition of the specimen geometry and reciprocal effects of cuts and holes. To exclude those effects, an ideal model was developed by applying uniform pressure on the cube specimen and making slots in a symmetrical way. The calculated strains agreed well with the measured strains in cube specimens having only slots on two sides. By analyzing cube tests using the ideal model, it was found that the strain relief by making slots in cube tests is related to the slot depth-to-spacing (SDS) ratio. The compressive vertical strains between the two slots decrease with increasing SDS ratio and reach to zero strain at the SDS ratio of 0.35. At the SDS ratio higher than 0.35, the strains between two slots become tensile.
Recommendations for Future Experimental Study:
In order to enhance the testing procedure for future experimental measurements, it is recommended to decrease the size of the concrete specimen so that a rectangular surface can fit in the 10” circular loading plate. To be able to apply uniform force on the entire concrete cube, a smaller size cube (7”x7”, 17.8 cm x 17.8 cm) is suggested. To prevent non-symmetrical behavior of the cube specimen, the same depths of slots should be made on the opposite side. The limit of the SDS ratio is suggested as the 0.35 since only the strain relief within the compressive regime is of interest. To maximize the efficient use of concrete cube, it is recommended to start with the smallest depth of slot.

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