Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

SPALL REPAIR USING A 3D PRINTER AND EPOXY RESIN ADHESIVE

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The spall repair sequence currently used is as follows. The damage is removed from the area with heavy equipment and fresh concrete is poured into the cleaned section. A curing compound is then applied to the patch to prevent drying shrinkage or to absorb water. But this spall repair method requires a great deal of equipment and time. During the repair process, adjacent roads must be closed in order to secure a working space, often resulting in traffic congestion. According to a report by the US Department of Transportation, the depreciation can be up to $20,000 a day due to traffic jams. The depreciation can easily reach up to $140,000 when a road is blocked for seven days to repair a spall. The objective of this research is to see if 3D printing technology can be used to repair spall damage on a concrete pavement. More specifically, this study, using a simple finite element method, investigates whether the bond line thickness will have an influence on shear strength development when an adhesive layer is present between the spall and the 3D printed concrete segment. In addition, this study proposes a modified test method of ASTM C882 to experimentally investigate the influence of bond line thickness of epoxy-resin adhesive on shear strength when the glue applied to a concrete adherend.

Keywords: Spall repair, Epoxy-resin, 3D printing, Bond line thickness, Concrete adherend, Shear strength.

1 INTRODUCTION

Joints, which are the edges of slabs of concrete road pavements, are often damaged by high-speed driving of vehicles or high compressive stresses of large vehicles. The palm-sized concrete damage is called a “spall”. The typical damage shape of a spall is as shown in Figure 1. If this minor damage is not properly restored in time, the damage will spread, and eventually, the structure of the concrete slab may be damaged (McVay 1988).

Currently, the partial-depth spall repair method is most commonly adopted in the field to fix spall damage on concrete pavement (Basham *et al*. 2001). Once the damaged area is separated from the undamaged area with a milling machine, the damaged section is broken up with a chipping machine and the concrete debris is blown away using an air compressor. Concrete is then poured into the cleaned section. To prevent water infiltration, the edges of the repaired area are filled with a waterproof agent. A white pigmented curing compound is then applied to the repaired area to prevent drying shrinkage or absorption of water. The areas rehabilitated by the partial-depth spall repair method are more stable and last longer than when the spall damage is filled with asphalt. However, it demands a great deal of equipment and time. In addition to the time required to fix the spall damage itself, one has to wait until the fresh concrete applied to the spall damage is fully cured. Time needed for the concrete hydration process varies depending on the cement type used, but at least a seven-day detour is required after the white pigmented curing compound is applied to the patch (Basham *et al*. 2001). While the repair process is taking place, the adjacent roads need to be closed to secure the workspace, and it often causes traffic jams. Traffic jams have a negative impact on the economy. According to a report from the US Department of Transportation (2015) up to a $20,000 loss can be assumed per day. If the road is blocked for seven days to repair spall damage on a concrete pavement, one can easily assume up to a $140,000 loss.

Figure 1. Beginning spall (Fowler *et al*. 2008).

2 MOTIVATION

Some dentists use 3D scanning and 3D printing technologies to fill cavities. As shown in Figure 2, they pick up the 3D geometry of the cavity using a laser scanner and print it out in 3D, which speeds up the cavity treatment process (Miyazaki *et al*. 2009).

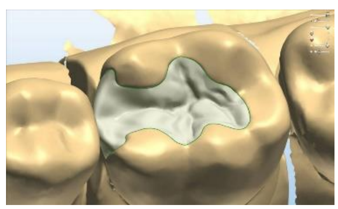

Figure 2. Filling a cavity through CAD/CAM technologies in the dental field (Carr 2009).

Could these technologies be applied to the spall damage repair process? The following procedure could be implemented if these technologies were applied to repair spall damage as shown in Figure 3. This paper suggests a new method to repair a spall on a concrete pavement using a prefabricated concrete segment tailored to the damaged area. The suggested spall rehabilitation method starts by: (1) scanning the spall using a 3D scanner; (2) creating the 3D model of the spall using point clouds; (3) printing a 3D model to use as a concrete form in which to cure fresh concrete; (4) pouring concrete in the formwork; (5) curing a concrete segment tailored to fill the gap; and (6) inserting a pre-fabricated concrete segment into the spall after an epoxy-resin adhesive is applied. This paper also presents what happens along the bond layer through the finite element method when this method is applied.

Once the spall damage is fixed with the suggested method and the road is reopened for users, the fixed area can be damaged again by traffic. When vehicles pass over the fixed area, a vertical force is applied to the concrete segment. If the strength of the concrete segment can handle the vertical force generated by the vehicles, and if there are no elevation differences between the fixed and undamaged areas, the vertical force would not harm the fixed area. However, when the torque generated by a vehicle that changes speed is applied to the fixed area, the stability of the fixed area would be determined by two factors: the strength of the concrete or the strength of the glue. If the strength of concrete were greater than the stress generated inside the concrete segment by the spinning wheel, the torque would not destroy the concrete segment itself. However, if the glue were not holding the concrete segment tightly enough, the printed concrete segmented would be ejected from the spall when the torque is applied. Various glues could be used to hold the 3D printed concrete segment to the spall surface. The bonding capacity of the glues that are used for the concrete surface is determined by at least two factors: temperature and thickness. Predicting the temperature range of a certain area is not difficult, and therefore one can choose the right glue that meets the specific needs of the location. However, the bond strength associated with concrete has never been examined when bond line thickness is changed.

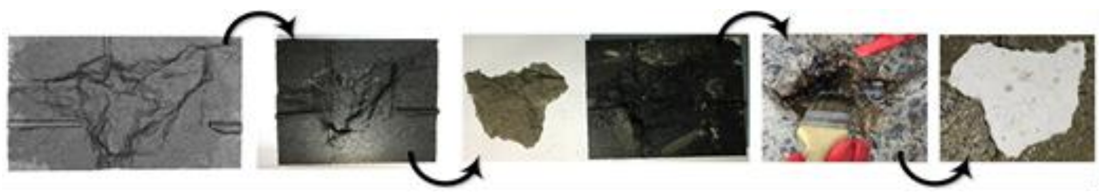

Figure 3. Spall repair method using 3D printing technology.

3 MECHANICAL BEHAVIOR

3.1 Damage Section Simplification

A spall has a complicated damage shape due to the bumps of aggregates. Also, the damage shape of every spall is different. Thus, the determination of the exact damaged section of a spall is nonsense in one form. However, the shape of a spall is similar to the shape of a bowl which has depth and an incline from the longitudinal axis of the concrete road from a vertical viewpoint. Hence, the shape of a spall can be simplified into an oval shape for the convenience of the analysis. Plus, the area of a spall is difficult to determine and the exact shape of a spall is hard to define. Hence, the shape of a spall can be simplified from a horizontal viewpoint as a circle in a rectangle for the convenience of the analysis. To help in understanding the damaged section simplification, Figure 4 shows the simplified damaged section from a 3D viewpoint. The transparent section shows the shape of the spall inside the concrete road.

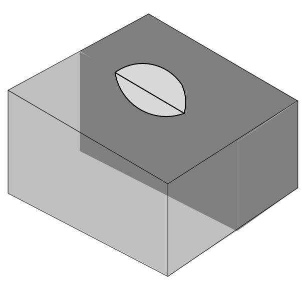

Figure 4. Spall simplification from a 3D viewpoint.

3.2 Simple Finite Element Method

To achieve the objective of this research, we need to know how the repaired area responds to applied stresses. If the concrete segment is just filling the spall without any applied stresses, it probably won’t change. However, something happens when a car accelerates on it. To know what happens between the concrete segment and the concrete substrate, a numerical analysis is carried out since it is difficult to know what happens on the glue layer between a spall and a concrete segment when a vehicle accelerates on a repaired area because concrete objects are opaque. Thus, a finite element analysis is carried out to explore the relationship of the interface. The primary purpose of the simple finite element analysis is to identify the major stress when a vehicle accelerates on a repaired area. Modeling a spall of real shapes and bumps is not easy. When the modeling of a real spall is completed, the numerical analysis results are for only one spall model. In other words, the finite element model, which has complicated shapes and bumps, cannot be used to identify the major stress. Thus, the concrete segment model is simplified as an oval shape. The relationship of the interface between the existing concrete substrate and a concrete segment is determined when a vehicle is accelerating on the repaired section. In this case, even though the shape of the concrete segment model is symmetric, the reactions on the interface can be different between the left slope and the right slope because this case considers that a tire of a vehicle is spinning on a concrete segment. Node 16 and node 12 are selected randomly in the middle of the left slope and the right slope that appear to be representative of the very center of each slope. Since there are many nodes, it is almost impossible to pick the exact center node of each slope. But the values can be representative of each slope. Node 16 was selected at the left slope of the concrete segment model to identify the major stress among the stresses occurring at node 16 when the tire is rolling from the left to the right. The determined major stress of the left node is the shear stress as shown in Figure 5. Node 12 was selected at the right slope of the concrete segment model to identify the major stress among the stresses occurring at node 12 when the tire is rolling from the left to the right. The determined major stress of the right node is shear stress, the same as node 12 as shown in Figure 6.

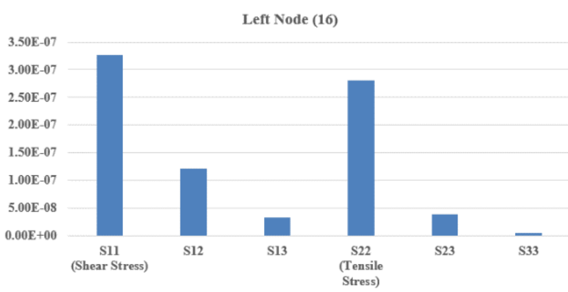

Figure 5. Occurring stresses at node 16.

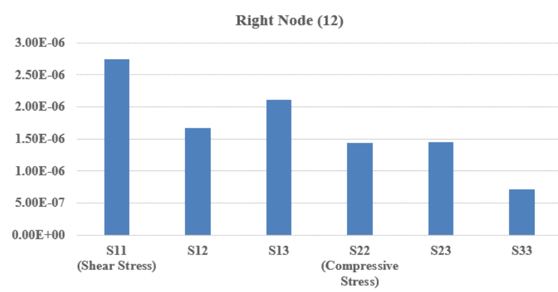

Figure 6. Occurring stresses at node 12.

The numerical analysis results showed that shear stress is the major stress when a car accelerates over a repaired area. In this case, the shear strength of the glue handles the major stress between the concrete segment and the concrete substrate because the glue works to bind them together. Both the concrete segment and the glue are important.

4 SLANT SHEAR TEST FOR EPOXY-RESIN ADHESIVE

4.1 Sequence of Concrete Specimen Preparation

The slant-shear strength is determined by the standard test method for the bond strength of epoxy resin bonding systems used with concrete (ASTM C 882 2013). (1) Preparing the Specimen: Concrete is poured into a mold to produce a specimen with various thicknesses of steel plates for securing the space for the glue layer. Here, a slanted slope is 30° as shown in Figure 7. (2) Applying the Glue: After curing the concrete, the steel plate is pulled off. After that, glue is poured into the gap that was left by the steel plate.

Figure 7. Specifications of a specimen mold.

(3) Placing the Specimen: The slant-shear specimen is placed on the universal test machine. (4) Applying a Load: A load is applied (2.3 ton/min) until the moment the glue layer of the slant-shear specimen begins to slide to determine the shear strength of the glue as shown in Figure 8.

Figure 8. Slant shear specimen.

4.2 Selected Epoxy-Resin Glue

Three epoxy resin bonding agents were used for this study. Bisphenol A (YD-128) was used as an epoxy and this epoxy is highly adaptable, resistant to chemical substances, and resistant to temperature changes (Kukdo 2004). Aliphatic amine modified type (KH 500) was applied as a hardener to make the first epoxy-resin adhesive. This hardener quickly hardens at room temperature, and its chemical resistance is excellent (Kukdo 2004).

5 CONCLUSION

The first epoxy-resin adhesive used bisphenol A and an aliphatic amine modified type. When the bond line thickness increases from 1 mm to 7 mm, the relationship between the shear stress and the shear strain appeared as shown in Figure 9. As a result, the shear stress came to the maximum value at 4 mm, but shear strength falls sharply at a bond thickness of 6 mm and was minimal at 7 mm. It also appears that the transverse displacement is less when the shear strength is high. This means that when the strength of epoxy-resin adhesive is strong, there is little displacement. Also, a brittle fracture appeared without signs of destruction.

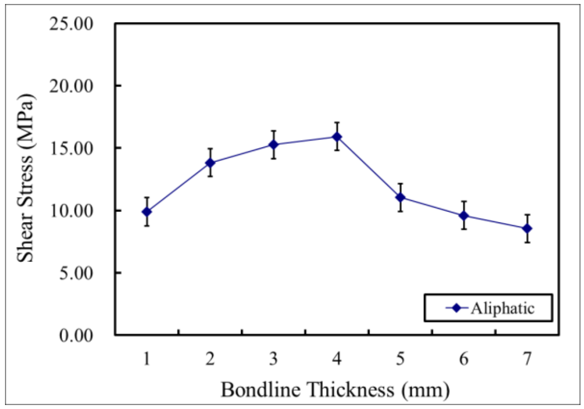

Figure 9. Shear strength of epoxy resin glue.

It has been found that it may be better to have some spacing rather than the concrete segments adhering completely to the spall. In other words, it can be seen that when the mold is created using the 3D printer, even some mechanical errors can be handled because the maximum shear strength developed when the bond line thickness was 4 mm.

6 FUTURE WORK

Future study needs to identify the stresses from the vehicle. This is to ensure that the shear strength of the adhesive is strong enough to handle the applied force. In addition, other epoxy resin adhesives should be tested for shear strength to determine whether those adhesives show the same tendency as the glue used in this study.

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