Spall Damage Repair using 3D Printers: Opportunities and Challenges

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Abstract
Palm-sized spall damage near construction joints on concrete roads is often caused by heavy vehicle. When spall damage occurs, the impact load from heavy vehicle is concentrated in the damaged area. As the damage is getting worse when it is left untreated, it needs to get repaired while damage is small. Common repair methods include placing fresh concrete and getting it cured. This method requires a minimum of 7 days for concrete hydration, which may cause an indirect loss of $ 140,000 according to the US DOT. This paper proposes an alternative way to repair spall damages by taking advantage of 3D printing technology. This method is about pre-fabricating a 3D concrete patch that can be inserted into a damaged area in less than 2 hours. This paper also presents how effectively an inserted concrete patch can resist the lateral loads caused by traffic.

Keywords
Spall Damage Repair, 3D Scanner, 3D Printer, Epoxy-Resin Bonding Agent

1. Palm-size Spall Damage on Concrete Pavement

Minor damages such as cracks, surface defects, and spalls that are taking place on the surface of concrete pavement are hardly avoidable (UDoT, 2003). Among those damages, cracks can be sealed relatively quickly with epoxy-based crack fillers (Caltrans, 2015). However, the spall damage repair takes a significant amount of time.

For palm-size spall damages, the partial-depth repair method is most popular as the result is more stable and lasts longer (UFC, 2001). The repair process begins with separating the damaged area from the undamaged area by sawing out the edge of the damaged area. The damaged concrete is then broken up and removed. Before poring fresh concrete into the damaged area, bonding agents are placed to improve the bond between the patch and concrete. Also, the edges of the undamaged area are coated with waterproof agent to prevent water infiltration. Once fresh concrete is pored into the damaged section and consolidated, curing compounds are applied to the surface of finished concrete to prevent concrete shrinkage. A typical repair process is represented in Figure 1.

Drying shrinkage takes place if concrete contains water even after the hydration process completes between cement and water. The remaining water will evaporate from a concrete patch, and it results in the reduction of concrete volume. Drying shrinkage of the concrete patch can lower the elevation of the repaired area, and ended up creating the elevation difference along the edge between the repaired area and undamaged area. The edge of the taller and undamaged area can easily get damaged by traffic because the dynamic loads from the vehicle are concentrated on the edge. In contrast, if the concrete patch absorbs water, the concrete patch may exhibit poor resistance to sulfate attack. The Unified Facilities Criteria (UFC) handbook issued by the U.S. military in 2001 recommend industry practitioners to wait for at least even days to protect the curing compound from any environmental attacks.

Figure 1 Mill-and-Patch repair method sequence (Source: FHWA, 1994)

2. Indirect Loss Caused by Detouring Vehicles

While the spall damages are getting repaired, the road is often closed and vehicles are supposed to detour. This vehicle detour often slows up the regional traffic, which ends up depreciating the value of those vehicles caught by traffic. The U.S. Department of Transportation (2015) estimated that the depreciated value of all those vehicles could be as much as $20,000 a day. Assuming that it would take at least 7 days to repair a palm-size spall damage, it is reasonable to estimate that we may lose as much as $140,000 indirectly because of this repair job.

Furthermore, it is not often easy to decide when the spall damages need to get fixed, because they don't seem to reduce the road usability significantly (NCHRP, 2004). In many cases, palm-size spall damages do not make drivers feel uncomfortable. However, palm-size spall damages on concrete pavement can cause a safety hazard because drivers can suddenly change the lane to avoid them (AASHTO, 1993).

3. Motivation

The conventional repair methods may not work well for palm-size spall damages, because they take time and use heavy equipment. Closing the road to repair palm-size spall damages is not making any logical sense. However, waiting until the spall damages grow enough is not making economic sense either. The repair cost can be significantly reduced if small spall damages get fixed on time before they grow.

Recently, the dental care industry started using 3D printers to fix cavities. They scan the contour of the cavity using a 3D scanner, create a 3D computer model of the filler optimized for a specific cavity, print the filler using a 3D printer, and then fix the cavity. This process enables a custom design, perfect fit, and shortened treatment process (Miyazaki *et al.*, 2009). Can this process be used to repair the palm-size spall damage on concrete pavement?

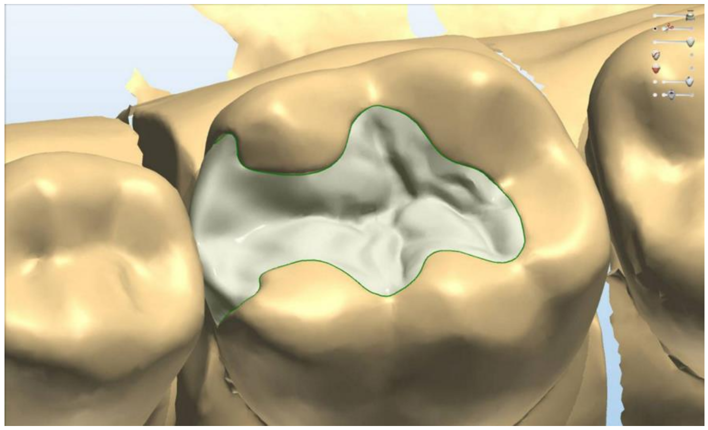

Figure 2 Filling cavity using 3D Printers (Source: Carr 2011)

4. Proposed Method

We propose the following method to fix the palm-size spall damage. Inspired by the practices going on in the dental care industry, our method pick up the three-dimensional (3D) geometry of the spall damage using a 3D scanner. Instead of printing the concrete patch in 3D right away, our method prints the plastic mold in 3D instead, which is used later as formwork for concrete placement.

1) Close the road to secure safety for field crews.
2) Pick up the point clouds of the spall damage using a 3D scanner.
3) Create a 3D computer model of the spall damage, as represented in Figure 3.
4) Create a 3D computer model of the formwork using the 3D model of spall damage.
5) Print a plastic formwork in 3D using a 3D printer.
6) Place fresh concrete in the formwork in a controlled space.
7) Cure the concrete segment in a way that shrinkage can be minimized and engineering property can be secured.
8) Remove the formwork and retrieve the concrete segment.
9) Bring the concrete segment to the job site.
10) Place a bonding agent on the concrete segment.
11) Plug the concrete segment into the damage area.
12) Open the road. This should be done shortly after the concrete segment gets installed.

5. Potential Challenges

This proposed method only works when the concrete segment sticks to the damaged area against any external load applied to the segment. To help the concrete segment adhere to the damaged area, a bonding agent is applied to the surface of the concrete segment. However, if the strength of the bonding agent holding up the concrete segment were not strong enough, the concrete segment would be expelled from damaged area.

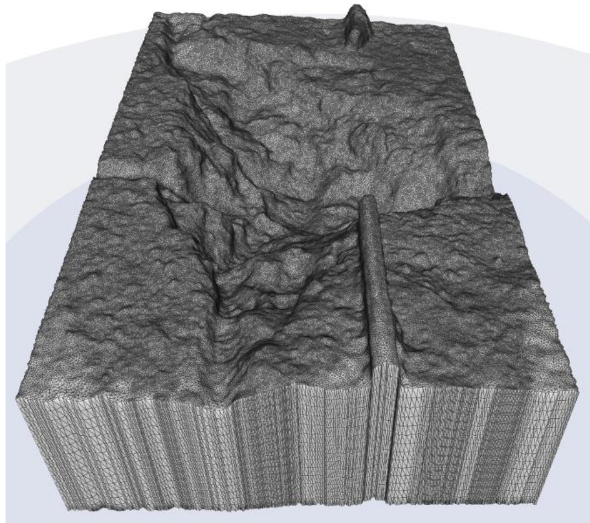

Figure 3 Typical spall damage presented in 3D computer model

Among many glue types, latex bonding agents and epoxy-resin based bonding agents are most popular in the construction industry (Mailvaganam 1997). These bonding agents are usually used to adhere concrete segments to an existing concrete surface. These bonding agents exhibit high strength and outstanding water proof (Mailvaganam 1997). The bonding agent is also the key to the structural longevity of the spall repair method. Hence, the proper bonding system should be selected for the proposed repair method.

5.1 Latex Bonding Adhesive

Basically, the bonding agents for the concrete segment require high strength and the agent should be able to bond hardened concrete to hardened concrete because this study fills a spall with a hardened concrete segment. But a latex bonding agent is improper for this purpose because it is used to bond fresh concrete to old concrete. There are four main latex emulsions based bonding applications for construction and the characteristics for each bonding agent are described below (Mailvaganam 1997).

Acrylic – This type of bonding system is used for bonding fresh concrete to old concrete and is appropriate for applying to indoor and outdoor damages, steel, wood, and a thin section topping. This type is improper for extreme chemical exposure and high hydrostatic pressure.

Polyvinyl-Acetate – This type of glue is applied to bond fresh concrete to old concrete and thin layer toppings. Also, this glue is appropriate for applying to indoor and outdoor damages, steel, wood, and thin section topping. This glue is improper for extreme chemical exposure and high hydrostatic pressure. Last, this type cannot be re-emulsified.

Butadiene-Styrene – this bonding agent can be applied to bond fresh concrete to the existing concrete structure and a thin layer topping. Moreover, this bonding agent is proper for use in indoor and outdoor damages, steel, wood, and a thin section topping. But this bonding agent is inappropriate for extreme chemical exposure and high hydrostatic pressure, similar to Polyvinyl-Acetate.

Polyvinyl Acetate – this latex bonding agent is for bonding to plaster and is used for indoor ceilings. This one is rarely used as a concrete bonding agent.

5.2 Epoxy-Resin Bonding Adhesive

According to the ASTM C881 / C881M-14, which is the standard specification for epoxy-resin-based bonding systems for concrete, these types are classified according to intended use (ASTM C881 / C881M-14 2015). Among these seven types of epoxy-resin-based bonding systems, Type IV is used as a bonding system for attaching concrete segments. Detailed descriptions of the adhesive types are shown below.

Type I - (Non-load bearing application) this type is used for bonding hardened concrete to hardened concrete and other materials.
Type II - (Non-load bearing application) this type is used for bonding freshly mixed concrete to hardened concrete.
Type III - Skid-resistant bonding materials for hardened concrete and as a binder in epoxy concretes used on traffic bearing surfaces.
Type IV - (Load bearing applications) this type is used for bonding hardened concrete to hardened concrete and other materials and as a binder for epoxy concretes.
Type V - (Load bearing applications) this type is used for bonding freshly mixed concrete to hardened concrete.
Type VI - This type is used for bonding and sealing segmental precast elements.
Type VII - (Non-stress carrying sealer) this type is used for segmental precast elements when temporary post tensioning is not applied as in a span-by-span erection.

Because of the tolerance of 3D scanning and 3D printing technology, it is not easy to produce a concrete segment that can fit the spall damage perfectly. A physical gap between the printed concrete segment and the spall damage is unavoidable. This gap is eventually filled with bonding agents and a bonding layer is created. Therefore, it should be investigated whether the bonding strength developed along the bonding layer is strong enough to resist the shear force generated by external forces.

Due to tolerances in 3D scanning and 3D printing technologies, it is not easy to create concrete segments that can be fully inserted into spall damage. The physical spacing between the printed concrete segment and the spall damage is inevitable. This gap is finally filled with a bonding agent and a bond layer is formed. Therefore, it should be investigated whether the bond strength developed along the bond layer should be strong enough to withstand the shear forces generated by external forces.

6. Conclusion

The proposed method for repairing palm-size spall damage uses 3D printing technology. After picking up the geometry of the spall damage, a plastic mold is printed in 3D. Fresh concrete placed in the model is cured in a controlled environment so that its engineering property can be secured. The entire repair process is completed by simply inserting the concrete segment into the damaged area. It is therefore reasonable to expect that palm-size spall damages can be fixed at their early stage without closing the road as the field operation can be completed within a few hours.

However, the entire repair process is not going to make any sense if the concrete segment installed in the damaged area gets expelled easily. The bonding agent applied to the concrete segment surface is supposed to hold up the segment against any external forces caused by traffic. According to the commercial vehicle weight standard defined by the U.S. Department of Transportation, the weight of the single axle of the container truck is 20,000 pounds (US DoT, 2003). It is necessary therefore to investigate what kind of forces would affect the stability of the fixed area, how the bonding agent would help the concrete segment resist to those external forces.

This paper introduced a method of repairing small spall damage using 3D printing technology. One of the advantages of this method is that it can finish the repair work in a short time. Instead of curing concrete at the site, concrete segments that have been cured are inserted between the damaged area, and repair work can be completed faster than conventional methods. With this method, traffic control that induces indirect losses can also be minimized together. Excellent engineering characteristics of concrete segments is also an advantage.

However, in the process of producing a damaged part into a 3D computer model using the photogrammetry technique, a process of manufacturing a plastic mold using a three-dimensional printer, and a process of curing concrete, the volume of concrete can be reduced. Therefore, space can float between the underside of the concrete patch produced and the damaged surface. This space makes the adhesive to be painted very much when putting a specific patch in the damaged part.

Damage repair method using pre-fabricated three-dimensional concrete segment also makes no sense if the concrete segment embedded in the damaged part easily unplugged the external load. The surface of the concrete segment sandwiched between the damaged parts can receive a vertical load of up to 20,000 pounds (US DOT 2003), a horizontal load of 16,000 pounds. Among them, the horizontal load is changed to the shear load received by the adhesive layer between the lower part of the concrete segment and the damaged surface. If the shear strength of the adhesive cannot withstand the externally applied shear load, concrete segments can come out of the spall damage. Therefore, it may be necessary to investigate whether the shear strength of the adhesive can withstand the lateral load caused by the truck.

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