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TECHNICAL AND ECONOMIC FEASIBILITY OF SELF-HEALING CONCRETE

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Abstract: Concrete cracking represents a major challenge in the concrete industry. Self-healing technique is an emerging technology that can minimize cracking at early stages on one hand and provide an opportunity to conduct a thorough repair at a later stage on the other. This study aims at achieving better understanding of the technical and economic feasibility of self-healing techniques when compared to conventional repair interventions. The study focuses primarily on developing a model that predicts the rate of crack propagation in self-healing in comparison with conventional concrete. This model covers a five year time span and induces twelve various crack geometry and characteristics. A simplified economic feasibility study is conducted taking into considerations anticipated cost of repair, type and extent of repair, cost of inspection, cost of usage disruption and the timely monetary value. For that, the cracking was studied in three scenarios: Initiating immediately after casting, five years after casting, and ten years after casting. This work reveals higher efficiency and economic merits for the self-healing techniques compared to conventional repair methods particularly for small cracking situations. It is recommended to expand this work to cover wider sets of self-healing techniques and cracks as well as implementing factors that can affect the healing percentages during service.

Keywords: - Cracks, Concrete, Self-Healing, Feasibility

1 Introduction

1.1 Concrete Industry

Concrete is the most frequently used construction material on planet earth because of its various advantages. Around 25 billion Cubic meters of concrete are used worldwide annually. Concrete usage is that frequent result from its comparatively cheap cost and the fact that it can be easily casted into several shapes (Bhattacharyya 2011). Concrete is also manufactured from highly abundant materials (Water, sand, gravel) and is highly resistant to fire (Reinke 2012). Although concrete has many advantages but the manufacturing process of concrete is not a sustainable process. Concrete production results in depletion of water and natural aggregates, high Portland cement consumption accompanied by high emissions of carbon dioxide (CO2) during its lifecycle process and also due to the large quantities of generated construction and demolition waste causing land-fill space depletion. As a consequence the concrete manufacturing is currently facing exceptional challenges to make it a greener material. (Meyers 2008).

There are two facts that can be guaranteed in case of any mix that can be called a concrete mix, the first fact is that it is going to harden and gain strength while the other fact is that no matter how of good quality the concrete is at some point of time it is going to crack.

1.2 Cracking effect on concrete

"Micro-cracks of width up to 0.2 mm do not impact the safety of the structure" (Jonkers 2011). Although most of the cracks do not usually affect the safety of the structure at the beginning, however they cannot be left neglected and untreated as cracks with time get deeper, wider and start forming large networks and that is when the safety and serviceability of the structure will be compromised. Also the appearance of cracks might cause some sort of public unsettlement despite the fact that the structure would be considered safe by construction experts. Additionally in case of some structures that has a high strategic value (nuclear reactor, dams, …..) even the smallest cracks cannot be tolerated. In order to prevent this from taking place the only option is that for each and every concrete structure continuous monitoring is essential and carrying out periodical maintenance and repair work is imminent.

1.3 Problems Facing Maintenance and Repair of Structures

Causes of concrete cracking are various (Shrinkage, Alkali-aggregate, reactions, fatigue, freezing & thawing) .Also inspection; monitoring and maintenance of structure are a necessary to keep the structure safe and sound. However the inspection and maintenance process is not always an easy thing to do.

1.3.1 Cost Consuming

Experts are required to carry out periodical inspection tests, special equipment are usually needed too in order to reach a reliable assessment regarding the condition of the structure and make the right decision about the right time for an interference to carry out the repair works. The types of labor that execute the repair works should be more skillful than ordinary labor the equipment used are more advanced and even the materials are more expensive. For instance the cost of maintenance and repair of concrete bridges in the US is nearly 4 billion dollars annually (Sierra-Beltran et al. 2014) and in Europe 50% of the annual construction cost is spent on repair and rehabilitation of already existing structures (Hilloulin et al. 2015).All this makes the repair process very cost consuming. There is also the indirect additional cost of disruption resulting from shutting down the structure even if it was partial during inspection and repair.

1.3.2 Time Consuming

The same applies to in case of time lost during both inspection and repair. In some types of structures like bridges the deck or at least some of the lanes should be closed and detours might be necessary, this causes traffic congestion and consumes a lot of time. This might also lead to some public unrest and frustration.

1.3.3 Inaccessibility of structures

Some types of structures cannot be accessed easily for inspection like underground tunnels or under water structures, in these cases very expensive and sophisticated robots are the only solution to provide an adequate and reliable inspection. The problem of inaccessibility becomes even more complicated during maintenance and repair, for instance in order to do some repairs for a dam, diversion of the water flow path might be necessary which of course might be impossible in some cases or at least very tiring and costly.

1.3.4 Not a sustainable process

Concrete is the second most consumed product on the planet after water. Repairing process is resource consuming and usually cement is required. The cement industry depends on heating limestone to produce cement; as a result cement production is regarded as the biggest contributor to all negative ecological effects of concrete. Research showed that the cement industry is responsible for nearly 5–7%

of total worldwide CO2 emissions (Hednriks et. al 2004). A conservative estimate indicates that for every 1 Kilogram manufactured a byproduct of 0.9 kilograms of carbon dioxide is generated. Other epoxies that are used in repair have negative environmental impacts and even some of them are hazardous to human health. In some cases even the inspection process might have some negative impacts on the environment too, for example using robots for the investigation of underground structures might result in disruption of the eco-system. “Also currently available repair systems are mainly based on environmental un-friendly materials such as epoxy systems, acrylic resins or silicone-based polymers” (Sierra-Beltran et.al 2014)

2 Back ground

2.1 Self-healing Concrete

“Self-healing is the property of a material to be able to heal or cure damages caused to it autonomously” (Bhattacharyya 2012). “The natural self-healing ability of concrete, known as autogenous healing, has been observed since 1836, it was initially discovered by the French academy of sciences” (Ferrara et al. 2013). The concrete’s ability to self-heal can be observed in older structures that have endured for long periods although they are not appropriately monitored or repaired. It was noticed that Cracks in the older concrete buildings such as Roman aqueducts and gothic churches have healed without any interference because the un-hydrated cement particles in the crack reacted with the moisture in the air producing a cement paste that sealed the cracks; however in newer structures the un-hydrated cement content is reduced, thus the natural self-healing effect has diminished. (Dunn 2011)

Although newer mixes possess better properties (higher compressive strength, better durability…), the ability of concrete to self-heal has decreased due to two main reasons. Firstly better and more efficient mixing processes result in less un-hydrated cement particles to react with moisture in air later, secondly the replacement of a portion of cement by other materials or additives such as fly ash or silica fumes.

Although the self-healing ability of concrete has diminished in newer mixes it will not be a smart choice to sacrifice all the other better properties only for better self-healing, that’s why the need for finding a method to enhance the self-healing ability of concrete has evolved. By enhancing self-healing ability three goals need to be achieved which are speeding up the process, increasing the frequency of self-healing to occur and sealing larger cracks.

2.2 Self-healing capsules

Self-healing capsules are capsules added to the concrete mix in order to enhance the self-healing process; they are usually composed of three components

2.2.1 Protective casing

It is the substance from which the outer casing of the capsule is made of. It must be chosen to be a water proof material that can withstand the mixing process without breaking and it should also be compatible with concrete so that it will not react with any of its components. The protective casing material should also possess lower strength than that of the concrete matrix as this will affect the crack propagation process, since cracks tend to change direction to pass through the weakest points. This means that capsules will act as a magnet that attracts the crack causing the capsule breakage which is essential for the healing process to start.

2.2.2 Healing agent

Mostly consists of a type of bacteria and a solution that the bacteria reacts and a buffer solution with to produce the sealant. This fills about 97% of the whole capsule volume. Several different types of bacteria have been tested, but commonly bacteria should be an alkali resistant type of bacteria as concrete is a highly alkaline material (PH value = 12). It should also be a spore forming bacteria with a long life span (>50 years) in order to last through the life time of the structure whenever cracks appear. Spore forming means that when the bacteria experiences unfavorable conditions they can get in a dormant state where they cannot reproduce but can survive for long durations. The selected type of bacteria should also be proven harmless to human health.

2.2.3 Nutrient

It is a solution added in the capsule for the bacteria to feed on when it is in an active state. The nutrient should also be chosen and tested carefully to guarantee that it is concrete compatible.

2.3 Self-healing process

The encapsulated bacteria capsules are added to concrete during the mixing process. As long as the capsules are sealed and the bacteria is not exposed to neither air nor humidity it remains in a spore state. When concrete starts to crack afterwards cracks tear the capsules that they pass through open. As bacteria get exposed to air they become in an active state. Also the cracks provide an easy path for water to penetrate the concrete. The bacteria starts a chemical reaction between itself, the nutrient and the water producing calcium silicate hydrate (CSH) which is cement paste like gel that seals the crack. After the crack is sealed the un-favorable conditions for the bacteria return so they get into the spore state again and the process is repeated if the same crack appears.

3 Methodology

3.1 Simulation model

A model was created to simulate the behavior of conventional concrete versus self-healing concrete after cracking starts and through a 5 year period based on an initial crack length ranging from (5 to 40mm) and width ranging from (0.25 to 1 mm). The model aims to:

- Compare the crack dimensions of both conventional concrete and self-healing concrete through a 5 year period if no repair takes place
- Compare the cost of inspection and repair in both case taking the additional initial cost of self-healing concrete into consideration.

3.2 Assumptions

In order to overcome the lack of information facing the authors in such a new field of research and to be able to successfully obtain results some assumptions were made:

1. Assumption of crack propagation within active crack propagation rate and less than severely deteriorated structures
2. The rate of crack propagation was assumed to be a 0.3mm increase in width and 5mm increase in length every 3 months. This particular assumption is based on field experience and discussions and assuming a worst case scenario, rather than documented results and previous research work. However, the authors believe that an arbitrary value needs to be set despite the fact that it can be challenged later on.
3. The percentages of healing values are based on literature review as scarce as it is. Nevertheless, one has to realize the difficulty in getting accurate values for percentage of healing in sight of diverse materials and conditions in each case.
4. Beyond a certain crack length, the crack moves form the stage of hypothetically linear elastic fracture behavior into non-linear non-elastic fracture behavior. This is accompanied by a doubled rate of crack propagation

3.3 Calculations & results

Healing percentage through a period of 3 months was calculated based on previous research based on 12 different initial crack lengths ranging between 5 and 40 mm and widths ranging between 0.25 and 1 mm as shown in Table 1

Table 1 Initial crack dimensions

Crack Width (mm)	Crack length (mm)
0.25	5.0
0.25	7.5
0.25	10
0.5	10.0
0.5	15.0
0. 5	20
0.75	15.0
0.75	22.5
0.75	30.0
1	20.0
1	30.0
1	40.0

The cost of 1 m3 of self-healing capsules is estimated to be around 5760 USD (Silva eat al. 2015). A dosage of 4% was assumed to be added to the concrete mix. This dosage was selected as this is the average added dosage in the research used to predict the healing percentage. This dosage is considered convenient as it will not have any negative impact on the concrete's mechanical properties and at the same time the probability of a crack passing through and breaking a capsule is high. This means that the cost of adding self-healing capsules to the concrete mix is estimated to be 230.4 USD/m3.

The decision to interfere and repair a structure in the model was based on a crack limit. This crack limit was selected to be when the crack length is equal to or exceeds 100mm and the crack width is equivalent to or exceeds 5mm. Based on the inspection if the length and width of a crack exceed the safe limit this means that an intervention to carry out repair works should take place.

The inspection and repair cost of conventional concrete was compared to the cost of using self-healing concrete while taking the initial cost induced as a result of adding the self-healing capsules during the production of concrete into consideration.

In order for the comparison to be on fair basis the time value for money should be taken into account, accordingly an interest rate of 8% per year (2% every three months period) was added to the initial cost of concrete. The model anticipated the cost of repair in both cases over three different time intervals. The first is in case cracks appear immediately after concrete pouring or secondly if cracking starts after 5 years of the concrete pouring occurred or finally if cracking starts after a period of 10 years after concrete pouring

As it will not be logic to repair only the biggest crack in the section and leave the other smaller cracks till they exceed the safe limit and do the repair procedure again causing new disruptions, thus the repair should be done for all structure or cracked section at once including the smaller cracks. This means that the cost comparison should be made for 1 m3 of concrete. The cost of concrete repairing 1m3 of cracked concrete was estimated to be 100USD in case of surface treatment, 147 USD in case of partial in depth repair and 200 USD in case of in depth repair. These values were based on previous research and on the experience of the authors.

Both the 3 values will be taken into account in the comparison, as for the same cracked section where a crack has exceeded the safe limit surface repair the crack density itself might be low so a surface repair would be done and as the crack density gets higher the decision to do a more in depth repair should be taken.

Inspection cost for strategic buildings was estimated to be equivalent to 0.25 of the partial in depth repair cost. Periodical Inspection was scheduled to be carried out once every three months in case of using conventional concrete. A periodical inspection taking place every 6 months was also scheduled in case of self-healing concrete and their cost was taken into account in calculations as this is still a new field; however the inspection periods can be further increased upon gaining a sufficient confidence level in self-healing concrete's performance.

Disruption cost was estimated to be equal to 3 times the cost of partial in depth repair this cost is considered convincing by the authors as shutting down a strategic building even if it was partial would result in high financial impacts on the economy.

4. Results and discussion

12 initial crack widths were assumed as shown in the table 1 to be the dimensions at which the crack will begin with and using the predicted percentage of healing the crack dimensions after a period of 3 months was calculated the final expected crack areas were as shown in Figure 1

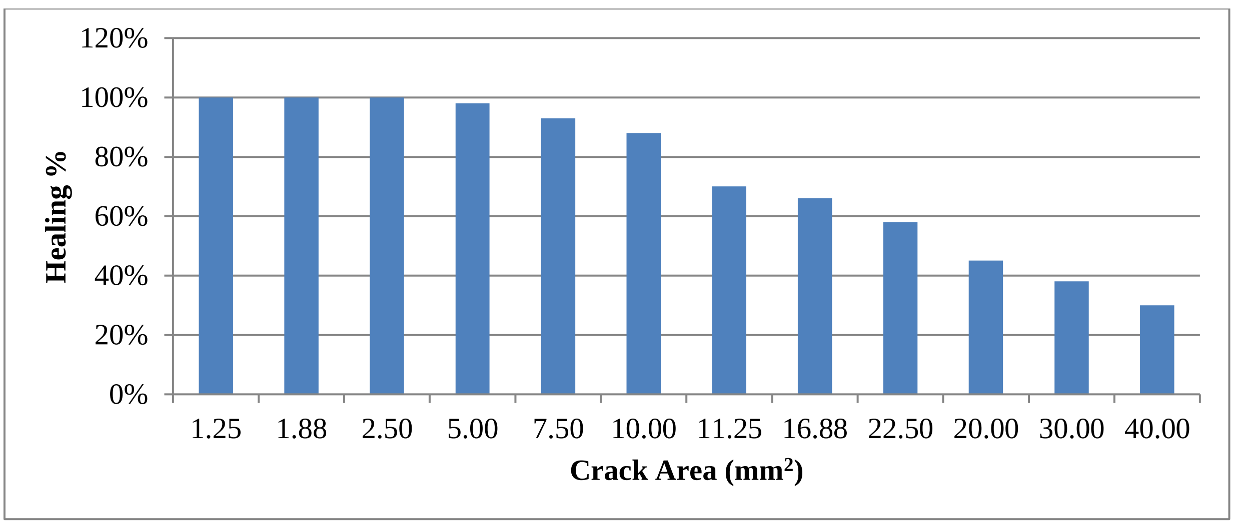

Figure 1 Expected healing percentage per crack area

Crack propagation was monitored every three months and over a period of 5 years. It was observed that two cracks exceeded the safe limit in case of conventional concrete after 42 months followed by another one in the following time period (after 45 months) and then 3 other cracks exceeded the safe limit after only 48 months have passed. On the other hand in the case of self-healing concrete the first crack to exceed the safe limit was after 48 months and the next one to exceed the safe limit was not until 54 months have passed.

The calculated final crack dimensions after a 60 months period “Table 2” showed that all the cracks in case of the conventional concrete have exceeded the safe limit with the biggest crack width reaching 8.8 mm and length reaching 170 mm while on the other hand only four cracks exceeded the safe limit and still they were in a better condition as the biggest crack width was 7.65mm and biggest length was 143 mm.

Table 2 Final expected crack dimensions after 5 years

Initial Crack		Self-healing concrete		Conventional concrete	
Crack width (mm)	Crack length (mm)	Final Width (mm)	Final length (mm)	Final Width (mm)	Final length (mm)
0.25	5	0.00	0.00	6.55	110
0.25	7.5	0.00	0.00	6.55	112.5
0.25	10	0.00	0.00	6.85	120
0.5	10	5.71	95.20	7.10	120
0.5	15	5.74	96.05	7.40	130
0.5	20	5.76	97.40	7.70	140
0.75	15	5.93	99.50	7.65	130
0.75	22.5	5.97	102.65	7.95	142.5
0.75	30	6.31	112.60	8.25	155
1	20	6.63	111.00	8.20	140
1	30	6.97	123.60	8.80	160
1	40	7.65	143.00	8.80	170

It is also clear that cracks with width of 0.25 mm have been healed completely after the first three months and no crack propagation occurred in case of using self-healing capsules

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The results of the cost comparison for the three time period for strategic buildings including the costs of repair, inspection, disruption and adding the interest rate show that Although the initial cost of self-healing capsules is higher but by the end of the 5 years it was found cheaper in all cracks and all types of repair (Figures 2,3,4).

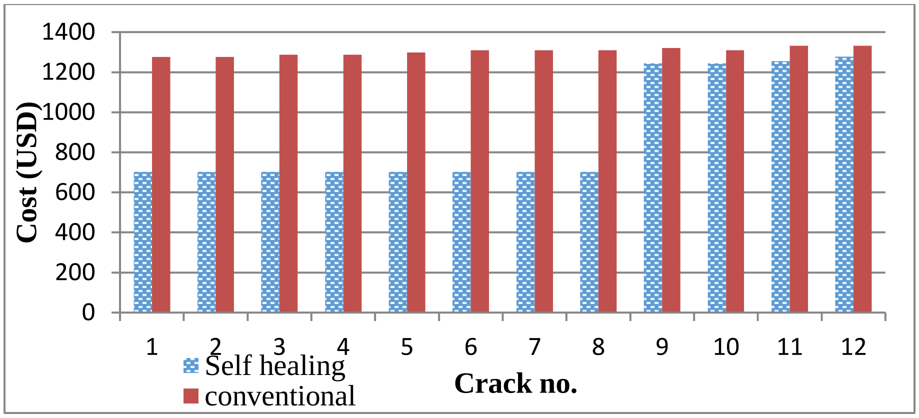

Figure 2 Final cost for self-healing VS conventional concrete (0-5) years

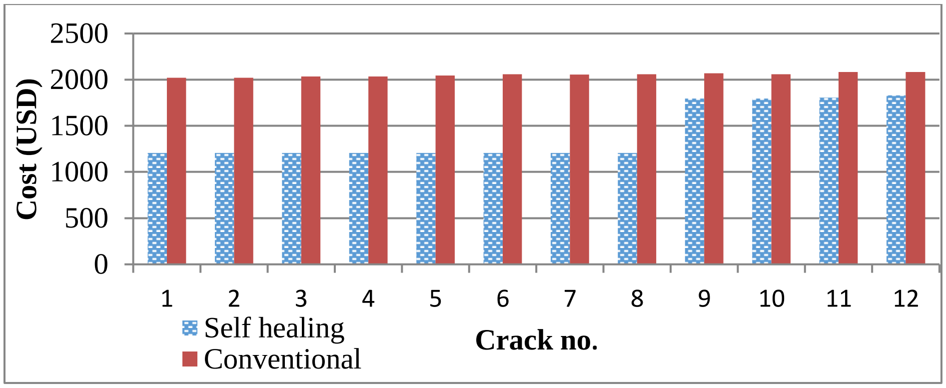

Figure 3 Final cost for self-healing VS conventional concrete (5-10) years

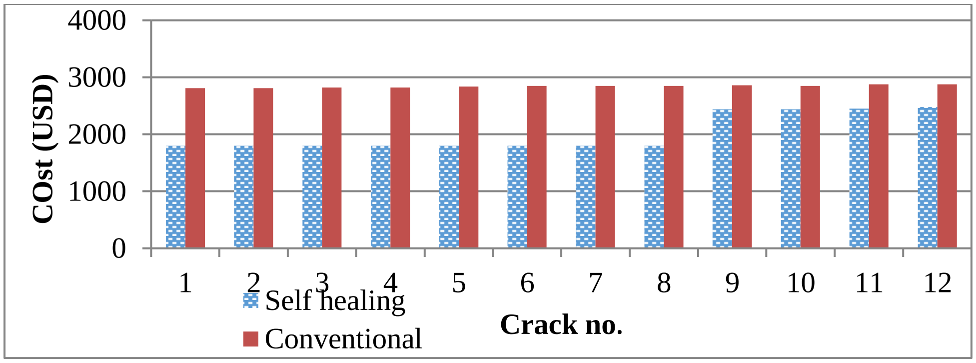

Figure 4 Final cost for self-healing VS conventional concrete (10-15) years

5. Summary, Conclusion and recommendations

The addition of self-healing capsules to the concrete for the aim of crack repair is a promising field. Despite the fact that a fairly good amount of research was conducted to prove that the addition of self-healing capsules has the ability to repair cracks no work has been carried out to prove the economic feasibility of this process. This work was carried out to compare the rate of crack propagation in case of using self-healing capsules with conventional concrete in case no repair takes place and also to compare the cost of inspection, repair and disruption for strategic buildings in both cases. In order to take the time value of money into account three what if scenarios were assumed expecting that:

1. Cracks will start immediately after concrete is poured and starts to harden
2. Cracks will appear after 5 years
3. Cracks will appear after 10 years.

Based on the parameters associated with this study the following can be concluded:

- The percentage of healing in case of the addition of the self-healing capsules decreases with the increase in the initial crack area which means that cracks with an initial width of 0.25 mm or less and length of 10 mm or less will completely be sealed.
- The expected percentages of healings are calculated taking into account that the concrete used in strategic buildings should be of high quality. If the quality of the concrete mix is not good the healing percentages will be lower.
- Cracks with bigger widths and lengths will not be completely sealed and the cracks will further propagate with time, thus periodical inspections still need to be carried out and cannot be omitted completely.
- The duration for the self-healing process to reach its maximum potential is around 3 months. This means that after 3 months have passed no more healing will take place even if the crack is not completely sealed.
- If no inspection or repair was carried out and for all cracks the final crack area at the end of the 5 year period is expected to be smaller in self-healing concrete compared to conventional concrete.
- Even for the cracks that exceed the safe limit in both cases and require a repair intervention the period for exceeding the crack limit will always be longer in case of self-healing concrete.
- As the disruption cost is always the highest cost to be incurred upon the repair of a strategic structure, so the repair process after any crack exceeds the safe limit should be carried out for all cracks and the type of repair (surface, partial or in depth) should be selected based on the crack density.
- Although the initial cost of the adding self-healing capsules to concrete is high, the final cost at the end of the 5 years for the first time period shows an expected saving compared to conventional concrete within 4% and up to 45%
- For the second time period (5-10) years the expected cost saving in case of using self-healing concrete is expected to be in a range of 12% to 40%
- For the third time period (10-15) years the expected cost saving in case of using self-healing concrete is expected to range between 14% to 33%
- The above trend shows that the percentage of cost saving increases when concrete cracking starts to happen after longer periods have passed if the initial crack area is bigger and the saving decreases with time for small initial crack areas.

1.1 Recommendations for future works

Similar to every work, there are several recommendations that could be taken into account for future work, some of the recommendations for future works would include:

- Coming up with more accurate expected percentages of healing can be more achievable upon carrying out more research in the field of self-healing and inducing the factors that affect the self-healing effectiveness in the model.
- Introducing crack depth as a factor in the geometry of the crack as although it is well established that there is a correlation between the crack depth and length but introducing the crack depth as a factor will still give more accurate results.
- A separate study carried out for more accurate simulation of rate of crack propagation instead of the linear rate assumed in this research would help in achieving more accurate results.
- A case study carried out using self-healing concrete would be of great help in gaining of a high confidence level in the performance in different weather conditions (temperature, humidity) and will accordingly give a more accurate insight on how frequent inspections should be carried out.
- A study for quantifying the environmental merits of using self-healing concrete could be carried out to highlight its benefits as a type of green concrete and would give other reasons for choosing it in addition to cost savings.
- Further study can be carried out to investigate the feasibility of using self-healing in repair of existing structures to find out if this would be cost effective.

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