A Study on Possibility of Application of Recent Self-Healing Methods for Self-Healing Concrete Railway Sleeper Manufacturing: A Review

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Abstract: Railway sleepers are under different types of dynamic, static, and impact loads. Due to a lack of a short span of track maintenance and inspection, damaged railway sleepers may not be detected and replaced after sudden damage. Cracks in concrete railway sleepers are almost inevitable and difficult to detect. According to the main role of sleepers to keep track of standard gauge and transfer loads to railway track interlayers, these damages may bring train derailment. Therefore, the application of self-healing methods can provide more lifespan time and compensate for some load capacity of damaged sleepers to extend their service life until they are inspected and removed from the track. Several self-healing methods have been proposed for large-scale beam shape structures, including autogenous and autonomous. But according to the special service condition of sleepers, most of these methods are not suitable for manufacturing railway sleepers. In this study, most of the available methods are reviewed and assessed based on the railway sleeper manufacturing process, service environment, loading condition, and lifespan. Finally, some prospective methods have been proposed to manufacture self-healing concrete railway sleepers such as the application of nanomaterials, vascular methods, and the LatConX system.

Keywords: Self-healing concrete; concrete railway sleeper; railway track

1 Introduction

One of the main roles of railway sleepers is to transfer loads coming from passing trains to the track interlayers [1-3]. Moreover, sleepers keep standard track gauge to avoid extra rails lateral displacement that may result in train derailment [4, 5].

Therefore, railway sleepers are one the critical components of railway tracks. Normally, track inspection is based on million gross tons (MGT) in some specific periods of time, unless an emergency damage causes emergency maintenance action [6, 7]. Damaged sleepers are detected using several methods such as measuring machine, ultrasonic, visual inspection, etc. [6, 8]. Therefore, self-healing railway concrete sleeper may avoid sudden failure of sleeper and compensate some load capacity of damaged sleepers to save track until next maintenance operation. Eequipping conventional sleeper with self-healing feature can increase the final cost a sleeper, but due to the healing process and avoiding the sleeper failure under operation it can compensate its higher cost [9].

1.1 Railway Concrete Sleeper Characteristics

Railway sleepers include timber, steel, concrete and composite sleepers [10, 11]. Concrete railway sleepers have been used extensively. Almost each year 20 million concrete sleepers are used in railway tracks construction [12]. These concrete railway sleepers are under static, quasi static, dynamic and impact loads that provide a complicated loading condition [13, 14]. Concrete sleepers have three main critical zones as positive bending moment zone in rail seats and nagative bending moment zone in middle of sleeper in which railway damages have been mostly observed, as shown in Figure 1.

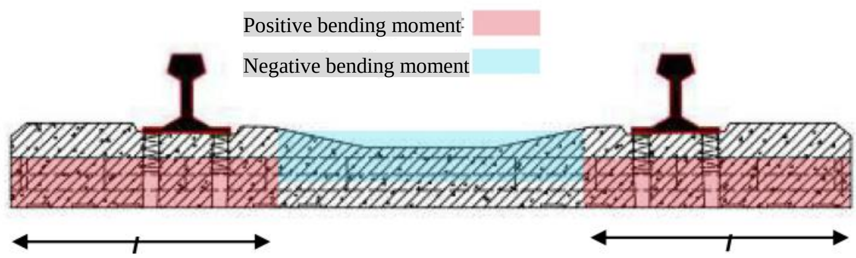

Figure 1
Critical zones in concrete railway sleepers [6] with potential of damage

1.2 Self-Healing Concrete Methods Classification

Self-healing concrete is mostly utilized for concrete composites that can repair minor cracks without the need for external intervention. Autogenous healing and autonomous healing are two types of self-healing techniques. Autogenous healing in concrete refers to the hydration of unhydrated cement. Autonomous healing, on the other hand, requires a trigger to start the process [15, 16]. Autonomous healing, unlike autogenous healing, relies on embedded atypical designed additions rather than unhydrated cement to fix bigger cracks. Autonomous healing strategies have outperformed most autogenous healing methods in crack healing [17].

Most autogenous healing methods are confined to cracks with a width of less than 150 μm.

1.2.1 Autogenous Self-Healing Methods

Table 1 lists some of the recent autogenous self-healing fracture repair techniques, including four categorizations as mineral powder, fibers, nanofillers and curing agents. Autogenous healing methods can heal crack up to 60%. The cracks mended by autogenously healing were observed in various diameters such as 0.05 mm to 0.87 mm, 5 to 10 μm, 100 μm, 200 μm, 205 μm and 300 μm according to the analysis and investigation of different authors [18].

Table 1
Overview of recent autogenous self-healing methods

Healing method	Sample dimensions	Healing materials	Crack width	Results	Ref.
Mineral powder	240 × 60 × 10 mm	Blast furnace slag and Limestone powder	60 μm	40%–60% healing for air cured specimen	[19]
	360×75×50 mm	Fly ash	< 100 μm	30 days of continuous moist curing was enough for specimens to achieve ultrasonic pulse velocity results higher than reference specimens.	[20]
	10Φ x 20 cm	expansive agent, geo-materials (montmorillonite) and chemical agents	0.22 mm	The 0.22 mm crack of concrete was self-healed at 33 days.	[21]
Fibers	360 × 75 × 50 mm	Carbon fiber	60-80 μm	Final healing improvement ranged between 2.3% and 5%.	[22]
	85 × 85 × 30 mm	synthetic fiber (polyvinyl alcohol (PVA) and hybrid fiber reinforcing (polyethylene (PE) and steel code (SC)	<0.1 mm	Only after the crack width was sufficiently narrowed by sealing the very tiny cracks around the bridging fibers could	[23]

				mechanical property be recovered.	
	25 × 25×100 mm	steel-fiber	20 μm	As the healing period increases from 0 to 14 days, the healing ratio increases from 9.4% to 36% for most multiple micro-cracks widths smaller than 50 μm.	[24]
Nanofillers	360 × 75 × 50 mm	Carbon nano tube	40-50 μm	Healing processed between 2.3% and 5%.	[22]
Curing agents	160×40×15 mm	PVA fiber, Superabsorbent polymer (SAP) (hybrid)	104 μm	Hydration was continued by absorbed water and to precipitate CaCO3.	[25]
	100 mm × 200 mm cylinders	saturated lightweight aggregates (SLWA)	–	The 11.0 % mixture is slightly more hydrated than the 55/0.30 combination because the 11.0 percent mixture contains a minor amount of additional water in the LWA.	[26]
	70 × 70 × 280 mm	water-saturated lightweight aggregate and super-absorbent polymer	–	The findings show that internal curing and a shrinkage-reducing additive work together to reduce cracking potential significantly.	[27]

	150 × 150 ×150 mm	Polyethylene Glycol	–	Healing concrete meet the minimum strength requirement as 25 MPa and even with strength much above 25MPa.	[28]

1.2.2 Autonomous Self-Healing Methods

Table 2 shows recent research in autonomous self-healing methods. Autonomous methods can heal wider crackes up to 1.16 mm, especially in vascular technique that more healing agent is provided in damaged zone. In micro capusl performance, shell which carries healing agent has a significant role. Some shells or cargos are easier to break and release the epoxy due to crack and followed by healing agent flows into the cracks due to a capillary effect, which is the flow of a liquid through a confined space without the aid of external forces such as gravity.

Table 2
Overview of recent autonomous self-healing methods

Healing method	Application method	Cargo	Crack width	results	Ref.
Electrodeposition technology	Electrolyte solutions + Direct current	$ZnSO_4$ and $MgSO_4$	0.3 mm ± 0.05 m	In this method the fastest crack healing speed is during the first 5 days and the cracks are completely healed after 20 days	[29]
	Electro chemical deposition treatment processes	$MgCl_2$ solution in an electrolyte	100 µm to 200 µm	Magnesium ions formed at the mouth of a surface-opened crack and continued to the crack Interface.	[30]
Shape memory alloy embedded technology	NiTi and NiTiNb shape memory alloy (SMA)	–	0.5 mm	The main crack recovery began at 75 °C and reached 73–100% in the NiTi, 38.7–74.1% in the NiTiNb specimens.	[31]
	deformed shape memory alloy fibers, NiTi and NiTiNb	–	–	The NiTi fibers showed the maximum enhancement of 67% after heat treatment.	[32]

Capsule technology	horone diisocyanate (IPDI) microcapsules	Araffin wax, polyethylene wax, and nano silica	Micro cracks	Concrete containing microcapsules exposed to sulfate attack provided a a shield in the pores after 14 days.	[33]
	epoxy resins microcapsules	St-DVB shell	Micro crack	The hardened epoxy bridged the cracks, as the dominant elements of C and O accounted for 95% of the mass in the surrounding cracks.	[34]
	dicyclopentadiene (DCPD) and sodium silicate	–	–	The modulus of elasticity of the concrete improved by 11% and 30% using sodium silicate, and the healing agent for DCPD microcapsules.	[35]
Vascular technolog	polymeric healing agents	poly(methyl methacrylate) tubes	1.16 mm	Chloride resistance was increased in cracked concrete beams using mixed-in capsules (glass or PMMA) packed with a water-repellent chemical.	[36]
	Methyl methacrylate	hollow glass tubes	–	In samples containing released adhesive, flexural toughening was increased for the second loading event, while most of the non-adhesive controls showed a decrease in flexural toughening.	[37]
	Cyanoacrylate, Sodium silicate	Heat shrinkable tube	–	In a 3-point bending test, the results reveal that pressurizing the network increases the flow of healing agents to the point where they fill the majority of a 0.2 mm crack.	[38]
Microbial technology	Bacteria	porous expanded	0.15 mm	The cracks healed using mechanism bacterial concrete	[39]

		clay particles		which occurs due to metabolic conversion of calcium lactate to calcium carbonate.	
	Microbial induced carbonate precipitation (MICP)	recycled concrete aggregates (RCAs)	0.6 mm	The average crack healing ratio was 71 %, while the crack area healing ratio was 84 %.	[40]
	bacterial powder and calcium source	Mixture of sulfo aluminate cement, fly ash, and iron sand powder	–	The carrier made from low-alkali cementitious materials may protect the loaded spores for at least 516 days.	[41]

2 Recent Studies on Large Scale Self-Healing Beam Shaped Structures

Because the crack width and service circumstances of large scale structures differ from those of experimental samples, a specific approach for providing self-healing property is required. Based on the polyurethane encapsulation that is integrated in the matrix with eight concrete mixes, Huang et al. [42] investigated an autogenous approach for manufacturing self-healing concrete sleepers. In the laboratory, artificial and man-made cracks have been generated. Modal impact excitation, ultrasonic pulse velocity, and visual inspection were used to track crack healing. According to the findings, modal impact excitation is the least effective method for crack monitoring, especially when the cracks are small. In another study, fracture development promotes capsule rupture, release, and subsequent hardening of the polyurethane inside the crack, according to Tittelboom et al. [43]. The second method involves mixing superabsorbent polymers (SAPs) into the concrete. These SAPs absorb water that enters the crack, swell, and close it. They also cause ongoing hydration and calcium carbonate precipitation when they release their water content later. Smaller cracks are more likely to heal than larger cracks, as seen in Figure 2. Crack closing ratios of 40-80% were found for crack widths of 0-50 µm, whereas ratios of 10-30% were obtained for crack widths of 200-250 µm.

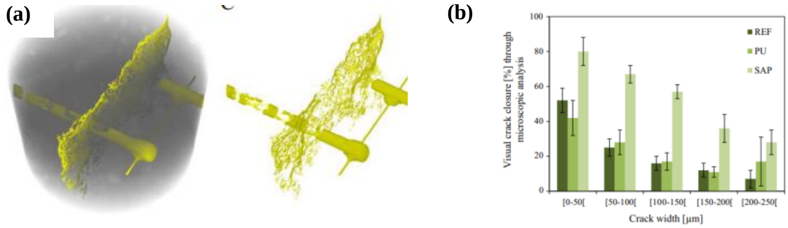

Figure 2
(a) Layout of long tube PU capsules, **(b)** Crack healing ratio [43]

Al-Tabbaa et al. [44] disscused a larger national effort to produce biomimetic cementitious infrastructure materials. In Fig. 15a, the daily average air temperature acquired from local meteorological stations is shown with the mean crack width recorded over the monitoring period. During the first four monitoring sessions, crack width readings consistently decreased between November 2015 and February 2016. The average normalised crack width is shown in Fig. 15b, along with daily rainfall totals. One of the most critical factors for successful autogenous self-healing is the presence of water.

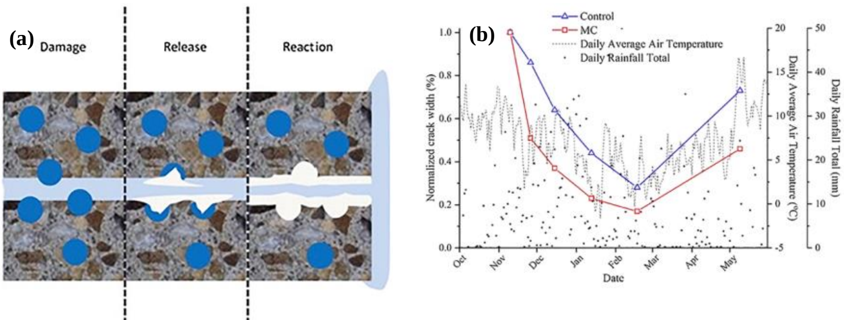

Figure 3
(a) A schamatic of self-healing capsules, **(b)** crack width measurements throughout the 6-month period [44]

The long-term behavior of a new self-healing concrete material system was compared to that of regular reinforced concrete by Hazelwood et al. [45]. LatConX (LCX) is a revolutionary material system that combines reinforcing steel and shape memory polymer (SMP) tendons within a cementitious matrix. The tendons' shrinkage process is activated when a beam has been cast, cured, and loaded, providing a compressive force to the cementitious matrix. Long-term simulations demonstrate the LatConX system's potential effectiveness in minimizing fracture widths in reinforced concrete structural parts. However, when a polymer shrinkage stress of 100 MPa is used and 50% of the damage is healed, the results reveal that a 65% reduction is possible.

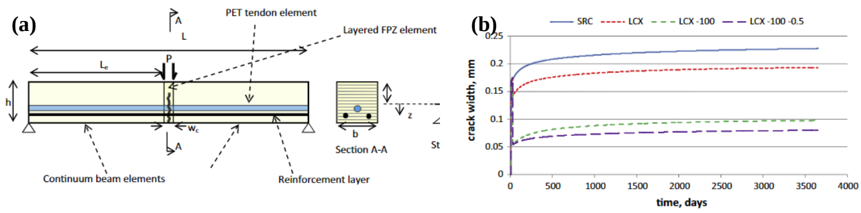

Figure 4

(a) A schamatic of self-healing beam, **(b)** Long-term behavior simulations of LCX beam [45]

The fracture process in self-healing concrete with implanted brittle capsules was explored by Dai et al. [46]. The validated numerical model reveals that the ratio of capsule slenderness to concrete-capsule interface strength is a critical characteristic for a successful self-healing process since it allows complete control over when the capsule breaks. The longer the capsule is, the longer it will take to break. Furthermore, increasing the length of the capsules has been found to assist improve the overall fracture energy of the beam, even after it has been fully broken (Fig. 5).

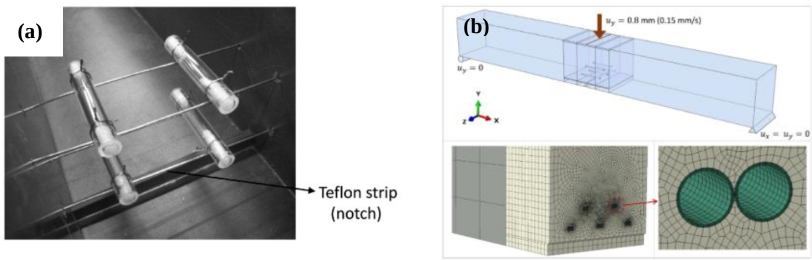

Figure 5

(a) An overview of tubes layout in the middle of beam, **(b)** schematic view of the healing tubes setup in numerical modeling [46]

Siahkouhi et al. [9] studied application of embedded different size PU tubes self-healing method to construct a self-healing railway sleeper. Final results showed that different size of PU tubes is needed in rail seat or middle of sleeper. Long tubes have a better performance in middle of sleeper and short tubes have a better performance in rail seat (Figure 6).

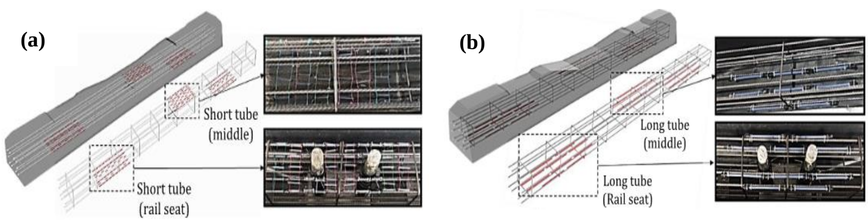

Figure 6

(a) short tubes at middle and rail seat, (b) long tubes at middle and rail seat of sleepers [9]

3 Compatibility of Self-Healing Methods for Sleeper Manufacturing

3.1 Manufacturing Process

In this section, differences between manufacturing of self-healing concrete and concrete railway sleepers are compared. Studying different methods through mix design, mixing and molding methods, and curing bring a bright overview of self-healing sleeper manufacturing.

3.1.1 Mix Design

By applying self-healing technology or incorporating the appropriate healing methods, concrete's ability to heal itself can be achieved and enhanced [47]. Typically, the conventional concrete mix design approach is used to calculate the self-healing concrete's mixing proportion [48]. However, some healing methods affacts the concrete performance, for instance, rheological performance of fresh concrete decreases in presence of geo-materials with swelling characteristics or other small particle size materials such as micro and nano materials [49]. The mechanical properties of concrete may improve or degrade depending on the circumstance when mineral admixtures are employed as a partial replacement for cement, resulting in a small drop in cement content [50]. Concrete mechanical strength may suffer with the addition of capsules [51]. Water/cement (W/C) ratios of 0.3 to 0.37 are considered in concrete railway sleeper mix design, resulting in low flowability and slump tests of 7 to 9 cm [52]. A small change in the mix design for sleepers can make a major difference in flowability.

3.1.2 Mixing and Molding Methods

The features of freshly formed and cured cementitious composites are significantly influenced by the method, speed, and length of the mixing process, according to earlier studies [53]. The fluidity and strength of cementitious composites are decreased while the number of pores in the matrix is increased by faster and longer mixing durations [54]. So it's important to use the right mixing and dispersion techniques. The most typical method of mixing is to place materials in a mechanical mixer until they are homogeneous enough [55]. Self-healing components that are brittle should be inserted into cementitious composites by the end of mixing to prevent them from damaging during production [56]. Brittle self-healing materials may have reinforcing steel bars, metallic wires, or fibers which are added during fracture formation to delay premature failure and reduce crack width [57]. To prevent breaking, capsules need additional protection, especially while combining [58]. In particular, for micro and nanoparticles with large surface areas and fibrous fillers with high aspect ratios, uniform dispersion of healing materials is necessary for significant self-healing capabilities [59]. Similar to conventional concrete, self-healing concrete can be molded. In order to obtain appropriate structural compaction, fresh concrete is frequently poured into molds in a number of layers, each of which is exposed to mechanical vibration [60]. Concrete railway sleeper consumes high amount of fresh concrete and has a high frequency vibration process. So in case of choosing self-healing method these parameters should be considered.

3.1.3 Curing

Water has been proven to be a critical component in improving self-healing performance in both autogenous and autonomous healing methods, and even high humidity is insufficient to ensure self-healing [34]. When pre-cracked mortars with mineral admixtures are dried in still water as opposed to flowing water, the permeability coefficient decreases more quickly and the crack width decreases more significantly. This is probably because flowing water eliminates calcium and hydroxide ions, reducing the pH and calcium ion concentration, both of which are necessary for the synthesis of healing products [61]. In terms of mechanical recovery, the water/air cycle curing method, followed by periodically renewed tap water, contributed to a superior self-healing performance of strain hardening cementitious composites [50]. Water curing compared with wet/dry cycles curing or wet curing, usually helps microbiological concrete in obtaining a greater fracture healing ratio [62]. Figure 7 shows how concrete railway sleepers are cured using steam and temperature. Maximum temperature increases to 90 ℃ for at least two days.

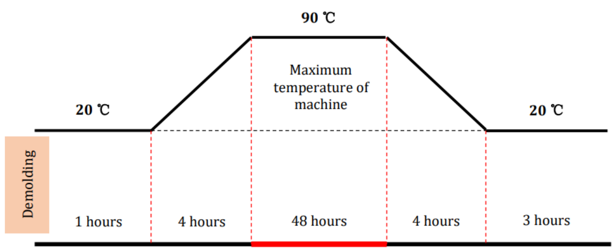

Figure 7
concrete sleeper curing method [52]

3.2 Self-Healing Methods Disscussion

Railway sleepers have been exposed to wear and weathering in a tough environment. Temperature, humidity, and other climatic conditions are highly variable in the region where sleepers are used, moreover, this structure is exposed to the sun without protection. As a result, this service condition precludes the use of several self-healing technologies, as shown in Table 3. Electrodeposition technology, which involves conductors (conductive concrete), electricity, and electrolytes, is particularly well suited to repairing marine concrete structures. Concrete's self-healing tendency with SMA requires thermal stimulation, but that with capsules or vascular is usually activated by crack formation. However, both autogenous and autonomous healing processes are highly capable of fixing cracks that are in micrometers scale width. However, some methods may be suitable to manufacture self-healing sleepers which are discussed in the following sections.

Table 3

An overview of contradiction between self-healing methods and railway sleeper production

<table>
<tr><th>No.</th><th>Self-healing methods</th><th>Contradiction with railway sleeper manufacturing</th></tr>
<tr><td>1</td><td>mineral powder</td><td rowspan="5">These methods provide self-healing property by more hydration to close cracks, for sleepers this water cannot be provided externally, unless in rainy places. Furthermore, presence of nanomaterials may influence on concrete flowability, especially in case of sleeper concrete with low w/c. These methods mostly are used for microcracks but in case of sleepers their crack sometimes is opened in mm scale.</td></tr>
<tr><td>2</td><td>fibers</td></tr>
<tr><td>3</td><td>nanofillers</td></tr>
<tr><td>4</td><td>Curing agents</td></tr>
<tr><td>5</td><td>mineral powder</td></tr>
<tr><td>6</td><td>Electrodeposition technology</td><td rowspan="5">The existence of micro capsules may decrease mechanical performance of concrete. Moreover, they may damage during mixing and manufacturing concrete railway sleeper. Healing material captive in cargo inside of concrete should not be influenced by curing temperature of concrete sleepers. Bacteria is not suitable for concrete railway sleeper manufacturing as it has short lifespan and needs special growing environment.</td></tr>
<tr><td>7</td><td>Shape memory alloy embedded technology</td></tr>
<tr><td>8</td><td>Capsule technology</td></tr>
<tr><td>9</td><td>Vascular technolog</td></tr>
<tr><td>10</td><td>Microbial technolog</td></tr>
</table>

4 Future Prospective

4.1 Self-Healing Tubes

One of the method which can be used for self-healing concrete sleeper manufacturing is application of vascular methods such as long and short tubes that can provide enough amount of healing agent [63]. Sleepers are under dynamic loads that can enforce agents captive inside tubes to come out and cover crack zone due to a capillary effect which is the flow of a liquid through a confined space without the aid of external forces such as gravity.

4.2 Nano Materials

Application of nanomaterials such as carbon nano tubes (CNTs) can be an option to manufacture self-healing concrete sleeper [6], just in case that external water can be provided for sleepers. So this method is not suitable for a desert area. Moreover, convenient to heal microcracks in long time.

4.3 LatConX System

The system comprises cementitious beams with Unbonded pre-oriented polymer tendons. When hydration reaction strarts due to the initial curing process, the crack is closed by thermally initiating the shrinking mechanism of the constrained polymer tendons [64].

Conclusions

This study reviews the potential self-healing methods to manufacture a self-healing concrete railway sleeper. First, these methods are categorized and then they are compared with concrete railway sleeper manufacturing process, lifespan and loading condition. Autonomous self-healing methods are suitable for higher crack width than autogenous, but they depneds on some inside triggers such as long and short tube PU encapsulation, micro capsules, LatConX system, bacteria etc. There are several parameters influence on application of self-healing methods to produce sleeper such as water that cannot be provided externally, unless in rainy places, presence of nanomaterials which may influence on concrete flowability, especially in case of sleeper concrete with low w/c, existance of micro capsules which decreases mechanical performance of concrete and they may damage during mixing and manufacturing, healing agents captive in cargo inside of concrete which should not be influenced by curing temperature, bacteria which has short lifespan and needs special growing environment. According to sleeper service condition, vascular method, LatConX system and application of nano materials can be suitable self-healing methods to manufacture self-healing sleeper. Although in a vascular method, high amount of healing agent should be supplied in fracture zone for crack healing.

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