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Self-Healing Materials to Enhance the Durability of Metallic Iconic Structures (Eiffel Tower as a Case Study)

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ABSTRACT
Iconic structures are very important because they provide the fame and aesthetic symbolism. It is crucial to take care of these structures in order to elongate their lifetime. This research is specifically concerned with the metallic iconic structures. Metallic structures are always exposed to corrosion. Corrosion is an attack on materials because of interaction with surrounding environment. In order to prevent metallic corrosion, innovative methods should be taken into consideration. Self-healing is a technique used in materials to repair damages and restore the properties and appearance of damaged parts.

Keywords:
Self-Healing Materials – Durability – Metallic Iconic Structures.

الخلاصة :
تعتبر الهياكل الايقونية مهمة جدا لانها توفر الشهرة و الرمزية الجمالية. لذلك فانه مهم الاعتناء بهذه الهياكل من اجل اطالة عمرها. يهتم هذا البحث بشكل خاص بالهياكل المعدنية الايقونية. تتعرض الهياكل المعدنية دائما للتأكل. التأكل هو هجوم علي المواد بسبب تفاعلها مع البيئة المحيطة. ينبغي منع التأكل المعدني عن طريق استخدام اساليب مبتكرة من اجل منع التأكل المعادني. الشفاء الذاتي هو تقنية تستخدم في المواد لاصلاح الاضرار و استعادة خصائص و مظهر الاجزاء التالفة.

Introduction

1 Metallic Iconic Structures

1.1 The Icon: History

'Icon. 1572. 1. An image, figure, or representation; a portrait; an illustration in a book; image in the solid; a statue. 2. Eastern Church: A representation of some sacred personage, itself regarded as sacred, and honoured with a relative worship' (Oxford English Dictionary).'iconic. An incitement to spend money' (anon. 2004)

The terms "icon" and "iconic" are often used to describe various cultural phenomena , especially in architecture. While some respondents rarely used these terms, many defined them as a combination of architectural novelty, visibility, and scale. Others view icons as structures that fundamentally change our perception of the world , both intellectually and emotionally. However, architectural icons differ from popular cultural icons, which require a harmonious combination of all elements.

Most buildings considered iconic are monumental in scale, but this is not the defining characteristic. Certainly, since the last quarter of the 20th century and the invention of new architectural glass technologies, translucency has become a common feature of iconic buildings, but it is certainly not the defining characteristic of iconicity.

1.2 Definition of Iconic Structures

Iconicity is a term associated with fame and aesthetic significance. Iconic structures are built to be visually attractive in addition to being used with their proposed functions. Here, the architect aims to increase the symbolic image of the building to be iconic. Iconic structures have unique features, can incorporate a special relationship with the place and people and are obvious in the city.

Iconic architecture is a contemporary trend seeking to create the ideal architecture in order to be a global image to achieve attraction and fame aiming to act as the monumental architecture and remain for generations. Famous architects such as Frank Gehry, Santiago Calatrava, Zaha Hadid, and Norman Foster have realized the importance of iconic architecture and built many examples of iconic buildings such as Heydar Aliyev by Zaha Hadid , Auditorio de Tenerife by Santiago Calatrava, Guggenheim Museum by Frank Gehry, The Gherkin by Norman foster, and much more examples that have influenced the field of architecture.

1.3 Metallic Iconic Structures

The elegance and functionality of metallic structures have defined the construction industry by inspiring architects throughout the twentieth century and the Industrial Revolution. The dominant metallic alloy over other metallic materials in construction is steel. Steel is an alloy of iron and carbon with improved strength and fracture resistance. Steel has many advantages as it has light weight, high strength, and takes less time to erect with the ease of design and construction. Steel structures express the modern architecture. Different types of iconic structures can be made of metallic alloys as shown in table (1).

Table (1): Examples of metallic iconic structures

<table>
<tr><td>Walt Disney Concert Hall, Los Angeles, USA</td><td>Centre Pompidou, Paris, France</td><td>Beijing National Stadium ‘Birds’s Nest’, China</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="2">Sydney Harbour Bridge, Sydney, Australia.</td><td>The Eiffel Tower, Paris, France</td></tr>
<tr><td colspan="2"></td><td rowspan="3"></td></tr>
<tr><td colspan="2">Guggenheim Museum , Nervión River , Bilbao, Spain</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Source: Arrow metal (Dec. 2017). The most iconic metal buildings in the world: Six of the best. Retrieved from https://www.arrowmetal.com.au/iconic-metal-buildings-world-six-best

2. Durability

2.1 Definition of durability

Durability is the measure of the performance of structures according to a certain period of time. There are two categories of durability: technical durability and functional durability. The interaction between materials and surrounding environmental conditions leads to the declination of the performance of all structures over time such as degradation of timber structure, and corrosion of steel. For any structure, there is a group of factors that influence its durability, such as type of structure system, type of material, and the pattern and frequency of use.

2.2 Deterioration

In general, metal corrosion is defined as the deterioration of metals due to exposure to corrosive environments, such as the atmosphere or even more corrosive environments such as seawater and chemical plants. There is no doubt that our daily lives are negatively affected by metal corrosion, as cars, buildings, infrastructure, household appliances, and electrical distribution systems are all susceptible to corrosion due to metal components. There is much debate about which pure metal or alloy is most suitable, but what is clear is that alloys can offer unique properties. For example, stainless steel, which is an alloy of iron, is more resistant to corrosion and has a slower corrosion rate than pure iron. In addition, it is an extremely strong and durable material with high impact resistance compared to pure iron. But that does not necessarily mean that the alloy is not subject to corrosion. So it can be said that corrosion of metals and even alloys is inevitable and needs to be prevented.

Thus corrosion is a crucial deteriorating mechanism and is considered one of the most dangerous types of metallic structures destruction. Corrosion is the reaction of the material with its environment leading to the remove of molecules from the material as shown in figures (1), (2), (3). The process of corrosion starts from the surface of metal and propagate deep into the material.

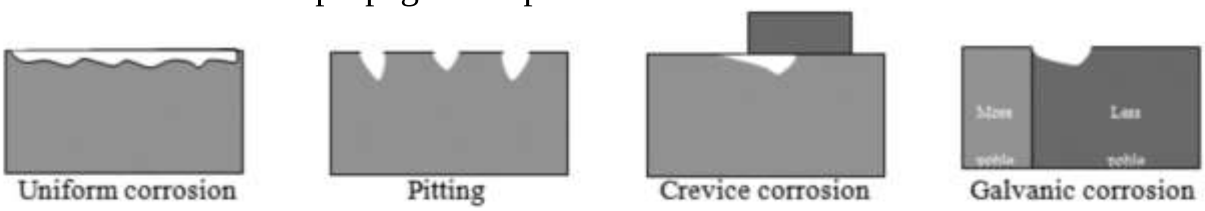
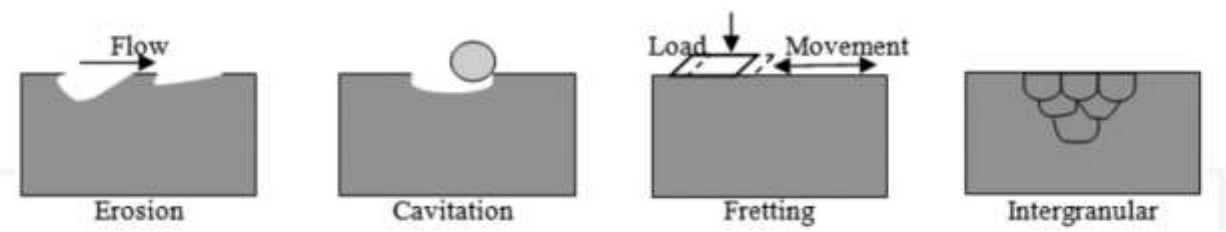
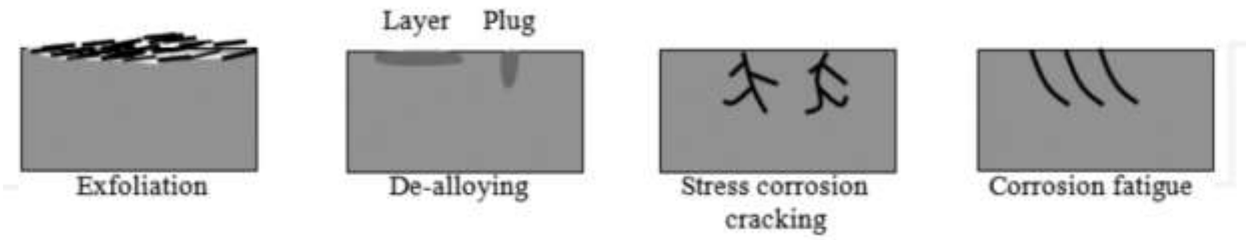


Figure (1): forms of corrosion identifiable by visual inspection



Source: Anaee, R., & Abdulmajeed, M. (2016). Tribocorrosion.INTECH.

Figure (2): forms of corrosion identifiable with special inspection tool



Source: Anaee, R., & Abdulmajeed, M. (2016). Tribocorrosion.INTECH.

Figure (3): forms of corrosion identifiable by microscopic examination

Source: Anaee, R., & Abdulmajeed, M. (2016). Tribocorrosion. INTECH.

In general, corrosion involves a complex series of chemical reactions and can be triggered by a number of different mechanisms, depending on the surrounding environment and involving simultaneous oxidation and reduction reactions. In practice, a water layer is first formed on the metal surface, followed by electrochemical and chemical reactions. In addition, corrosion products can participate in these reactions. The mechanism and rate of the chemical reactions that lead to corrosion depend on the corrosive factors in the surrounding environment, which gives rise to different classifications of corrosion. The most important factors contributing to metal corrosion can be classified as follow:

- Gases (CO2, SOx , HCL, HF, H2SO4, NH3, H2S, etc.)
- Moisture, dew, and condensation
- Temperature
- Relative humidity
- Type of metal
- Acidity and alkalinity (pH)
- Corrosive ions (Cl−, SO42−, Mg2+, etc.)

Corrosion can lead to severe consequences in finance and safety due to the loss of material and strength of structural members. A serious consequence that results from corrosion is the collapse of structures. An example of structure collapse due to corrosion is the silver bridge. In 1967, the silver bridge in Virginia state collapsed due to stress and fatigue corrosion of connecting elements, figure (4), (5).

Figure (4): silver bridge before collapse
Source: Choudhury, J.R., & Hasnat, A. (2015). Bridge collapses around the world: causes and mechanisms. IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III.

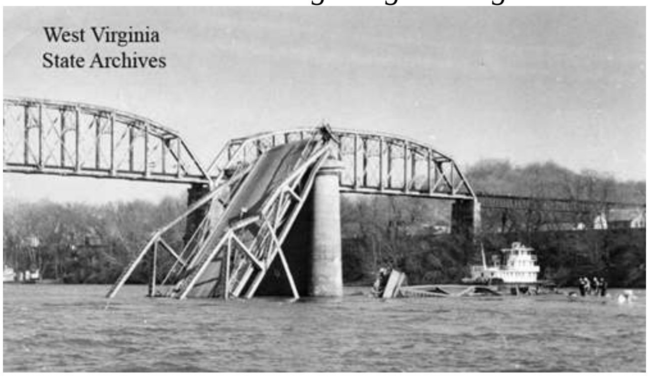


Figure (5): collapse of silver bridge in Virginia state USA
Source: Brumage,J. (2017). The legacy of the collapse of the silver bridge. Retrieved from https://www.byrdcenter.org/blog/the-legacy-of-the-silver-bridge-collapse

2.3 Enhancement techniques

Corrosion can lead to weakening the structure over time. So, maintenance and protective procedures should be applied to the metallic structures in order to enhance their durability. There are many protection methods as illustrated in figure (6). Selecting the appropriate method depends on cost, effectiveness, type of metal, corrosive media... etc.

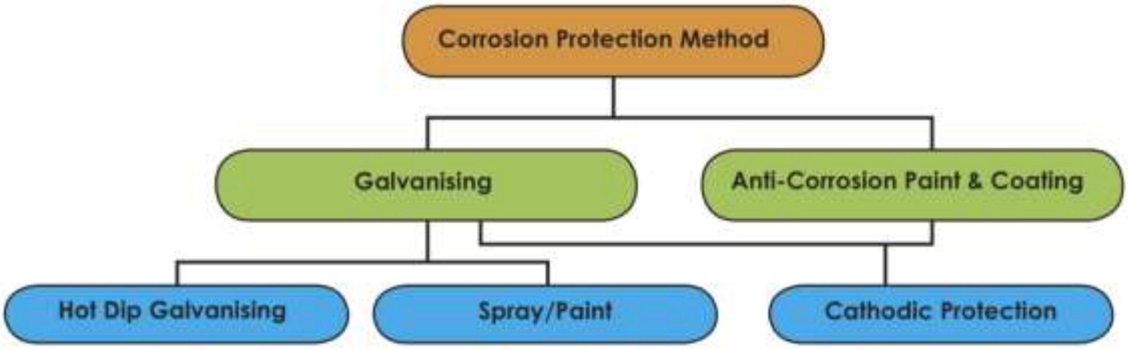


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Figure (6): Corrosion protection methods
Source: Building and construction authority, (2008). Sustainable construction: a guide on corrosion protection for steel structures.

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3. Self-Healing materials

3.1 Definition of self-healing materials

Self-healing materials are smart materials that include sensors and have the ability to adapt to external stimuli, such as light, temperature, pressure, humidity, electric field, magnetic field, chemical environment. Self-healing materials can act like living organisms as they have the ability to recover, repair damages, and restore their properties and appearance leading to their longevity and stability. So self-healing materials can heal (restore/repair) internal damage automatically and autonomously. This is certainly a truly amazing feature, being able to fill not only cracks but also tiny pinholes. Different types of materials, including polymers, metals, and ceramics, can have the ability to self-heal through their self-healing mechanisms.

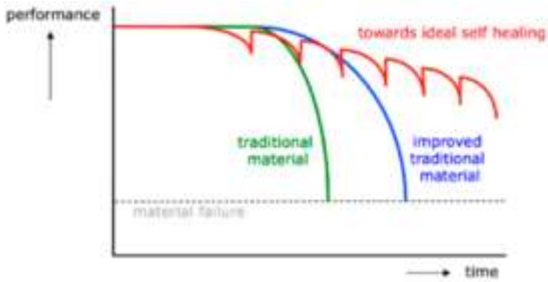

Figure (7): performance of self-healing materials relative to time
Source: NL Agency (2011). Self-healing materials: concept and applications (second edition).

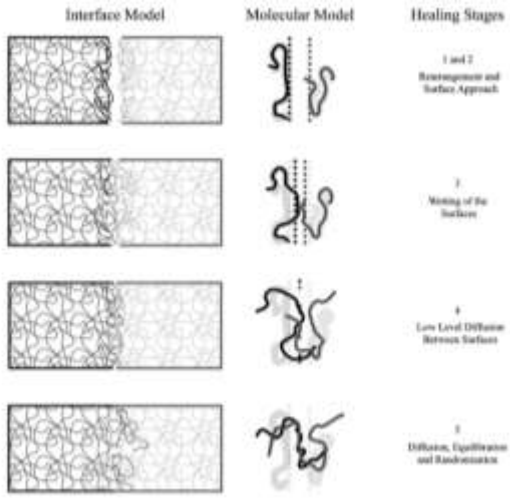

Figure (8): mechanism involved in self-healing via molecular inter diffusion
Source: Kalantari, S., Adimi, N., &Azmoudeh, A. (2020). The role of self-healing materials in architecture with a sustainability approach in buildings. Second conference on environment, Padua, Italy.

3.2 Mechanism of self-healing materials (Metal corrosion and self-healing)

Self-healing materials are protective coatings that can seal, close defects, and prevent the corrosion reactions at the coating defects of metallic structures. This requires adding micro capsules loaded by a polymerizable healing agent or corrosion inhibitor to routine binders. These coatings are epoxy or polyurethane-based organic systems. There are two mechanisms of self-healing coatings: autonomous and non-autonomous based on the ability to repair their integrity and functional properties with external physical interventions with external stimuli such as light and heat.

3.2.1 Autonomous healing mechanisms

Autonomous self-healing coatings are capable of recovering their overall integrity and/or functional properties without any external physical intervention. The ability to heal autonomously is typically achieved by embedding an exogenous polymerizable healing agent into the coating. In this system, the pharmaceutical agent is typically stored in microcapsules and is released when the coating is damaged. This then polymerizes to fill the damage or form a protective film that inhibits the electrochemical reactions that occur on the exposed metal substrate.

3.2.2 Non-autonomous healing mechanisms

In non-autonomous systems, the healing effect is achieved by an external stimulus such as heat or light, which triggers the chemical reactions and physical transitions required for bond formation and molecular chain movement. In effect, these types of coatings cure by restoring the inherent chemical bonds and/or physical configuration of the polymer network in the coating matrix. The external stimulus provides the activation energy required for bond breaking/bond reformation. For example, a thermal stimulus can bring broken bonds closer together, enhancing their reactivity.

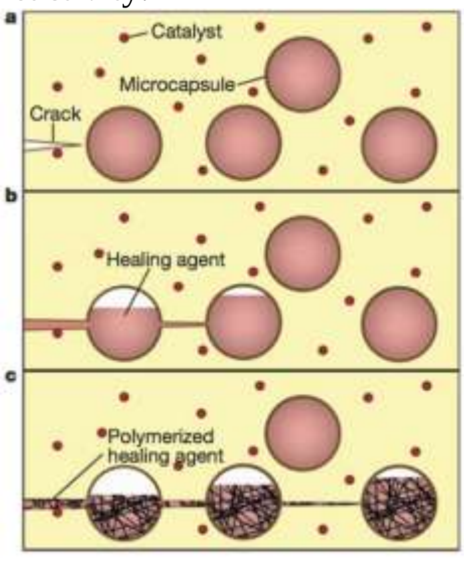

Figure (9): The autonomic healing concept. A microencapsulated healing agent is embedded in a structural composite matrix containing a catalyst capable of polymerizing the healing agent. a, Cracks form in the matrix wherever damage occurs; b, the crack ruptures the microcapsules, releasing the healing agent into the crack plane through capillary action; c, the healing agent contacts the catalyst, triggering polymerization that bonds the crack faces closed.

Source: R. White, N. R. Sottos†, P. H. Geubelle, J. S. Moore, M. R. Kessler, S. R. Sriram, E. N. Brown & S. Viswanathan, " Autonomic healing of polymer composites", Nature journal Published: 15 February 2001

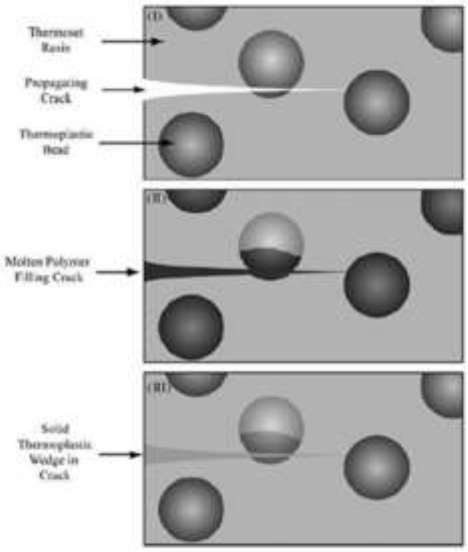

Figure (10): Non-autonomous healing mechanism. Depiction of the immiscible thermoplastic particles incorporated into a thermosetting system and healing mechanism.

Source: Athanasios S. Kotrotsos, "Development of Self-healing Techniques for Fiber Reinforced Composites" , Doctor of Philosophy Dissertation , University of Patras School of Engineering Department of Mechanical and Aeronautical Engineering Applied Mechanics and Vibrations Laboratory. May 2017

Case Study

4. Eiffel Tower

4.1 Structure analysis

Eiffel Tower is a good example of corrosion prevention and control.

- Place: Paris, France
- Construction year: 1889
- Material: more than 18,000 pieces of wrought iron
- Height: 324 m
- Anticipated useful life: 20 years
- Age: 120 years

4.2 Corrosion control

The traditional corrosion control method that is used since its construction is the separation of the ionic conductor from the rest of the elements through coating system every seven years. The parts of the tower are either with coating damage and surface corrosion or with severe corrosion. Manual application of 60 tons of two-layer urethanized alkyd resin-based coating for parts with surface corrosion. Parts with severe corrosion are replaced by new parts. During the lifetime of Eiffel Tower, it has been coated more than 19 times, every seven years, with a maintenance program applied to it. 60 tons of anti-corrosion coating are applied to the structure during an 18-month renovation period at a cost of 4 million euros.

Figure (11): corrosion in the metallic structure of Eiffel Tower
Romero, G. (Jan 2022). Eiffel Tower: the Iron Lady. Retrieved from https://inspenet.com/en/articulo/eiffel-tower-the-iron-lady/

Figure (12): maintenance of Eiffel Tower
Romero, G. (Jan 2022). Eiffel Tower: the Iron Lady. Retrieved from https://inspenet.com/en/articulo/eiffel-tower-the-iron-lady/

4.3 Comparison between anti-corrosion and self-healing coating of Eiffel Tower

From the study it is clear that the frequency of using self-healing coatings is less than that of anti-corrosion due to the ability to repair damages. So, the amount of coating used during the lifetime of the structure is less when using self-healing materials leading to reducing the overall costs of coatings.

Conclusion

Iconic structures are very important. Their importance requires prolonging their lifetime through resisting surrounding circumstances that lead to their deterioration. One of the famous technologies nowadays is self-healing material. Self-healing materials should be used in places where durability is essential. Structures can be coated with self-healing materials to enhance the anti-corrosive

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performance and service life. Manufacturing of self-healing materials is more expensive than traditional materials. During the structure lifetime, self-healing material is less expensive due to the fewer coating times.

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