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Review

A review of the use of stainless steel for masonry repair and reinforcement

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HIGHLIGHTS

- This paper analyses retrofitting methods based on the use of stainless steel.
- The chemical stability and the compatibility with masonry make stainless steel suitable for unprotected applications.
- Stainless steel bars, cords and profiles have been used to reinforce or repair masonry members.
- Reinforced structures presented enhanced behavior and increased structural response.

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ABSTRACT

This paper focuses on the recent evolution of the utilization of stainless steel profiles for repair and reinforcement of historic masonry structures, which are often subjected to dynamic in-plane shear and out-of-plane loading when struck by an earthquake. The conservation of the building heritage affords many challenges to structural engineers and architects. Increase in static and dynamic load-capacity, compatibility of repair materials with historic masonry material, reversibility of reinforcement interventions, limited increase in mass, preservation of the fair-faced aspect of the masonry are examples of common issues showing the complexity of the design problem. The use of stainless steel alloys in structural engineering applications is not a new idea, but civil engineers have a limited knowledge of these alloys. This paper sets out the development of the retrofitting methods based on the use of stainless profiles and presents a review of experimental studies carried out into the mechanical behaviour of masonry structures reinforced using stainless steel. A number of cases are considered and discussed (shear reinforcement of wall panels, crack stitching, transversal connection of multi-leaf walls and retrofit of towers and chimneys) and conclusions are drawn from the reported studies.

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1. Introduction

Stainless steel components are used increasingly for structural applications, mainly for new constructions. However, the term stainless steel is confusing as it refers to a large number of diverse alloys with substantial different mechanical properties. There are three main alloys used for structural applications: the ferritic, the austenitic and the more recent duplex stainless steels [1–3].

With regard to the use of stainless steel for repair and reinforcement of historic masonry constructions, there are many desirable characteristics which can be exploited in a wide range of construction applications.

The chemical stability (i.e. the characteristic corrosion resistance), the specific strength (material's strength divided by its density), the compatibility with historic masonry make this family of alloys suitable for outdoor, unprotected applications, in seismic prone areas and this class of materials of interest for structural engineers and conservators for a significant number of possible applications.

First applications of stainless steel date back to the beginning of the 20th century, when the use of austenitic steel alloys was first experimented. An example of an interesting early application is the steel tie used to reinforce and stabilize the dome of St Paul's Cathedral in London in the 1920s [4]. For some reasons, the engineering community has paid more attention to the use of FRPs (Fiber Reinforced Polymers) and very little, by comparison, attention to the use of stainless steel, when the latter material has been in the market for longer time and in many applications. The similarity of stainless steel with more traditional steel (having less novelty and thus producing less interest), the initial high cost of these alloys, the common exaggerated belief of the outstanding properties of FRPs, the stronger commercialization of the FRP products for repair and reinforcement of masonry structures can be likely considered as the main causes of this lack of attention.

However, the annual consumption of stainless steel alloys recently increased dramatically, surpassing the growth rate of other materials, and approximately 14% of this is now used in construction [5].

In this context, the conservation of the architectural heritage became, especially in Europe, an important issue, given its value in terms of social, cultural and economic history. Some historic structures, because of their importance, are often protected by being in the guardianship of the state or local authorities (Conservation Bodies, Municipalities, Regional Governments); these structures are mostly masonry structures dating from before 1920s. Local authorities always require to use a repair and restoration practice designed around the principal aim of preservation of as much of the original masonry structure as possible (Minimal Intervention), to use compatible new materials and reversible retrofitting methods (i.e. reinforcements should be removable without damaging the pre-existing masonry).

The high seismic hazard level of south-east countries of Europe and the need for cost-effective solutions are other critical factors to consider for successful reinforcement and repair of historic masonry structures [6,7]. However, effective retrofitting methods are sometimes the antithesis of compatibility and reversibility, and structural engineers have to find creative compromises. This encouraged research on the use of new materials and methods for repair and reinforcement of buildings.

The importance of this field of research has been also recognised through recent strategic investments in research and skills, supported by the European Commission (Horizon H2020 call) and national government funding (ReLuis in Italy, Heritage Lottery Fund in UK, Aristion project in Greece, etc.).

One critical factor to consider is the very poor quality of historic masonry material used to construct ordinary buildings. It is known that masonry has a good structural response in compression but has very limited shear and tensile strengths. Poor-quality masonry (i.e. rubble and pebble stone masonry, constituting multi-leaf walls assembled with inconsistent mortars made with a natural aerial lime) is very common in historic constructions.

This often limited and made difficult the engineers' work. In many applications, the solution was to use FRPs, often composed of thin fibres of carbon and glass, bonded with strong adhesives (i.e. epoxy resins) to the deficient masonry material. Several studies demonstrate that it is possible to reinforce or repair masonry structures using composite materials.

However, more recently, research addressed the problem of durability and the sustainable characteristics of composite materials when used to reinforce historic buildings and a number of criticisms were raised: poor compatibility with standard construction materials, reduced durability of the resins, fibres degradation, reliance on oil (both carbon fibres and epoxy adhesives are made from a pitch derived from oil processing), unsatisfactory outcomes of the Life Cycle Assessment (LCA), health and safety issues, difficulties in removal (reversibility) [8–11].

For these reasons, conservation bodies and local authorities often prohibit or limit the use of organic (epoxy) adhesives and composite materials on buildings under their supervision.

The use of stainless steel can solve some of the above problems. Stainless steel reinforcement is usually applied by means of mechanical connectors (without the use of resins) or embedded with lime mortars, its degradation on the long-term is much lower compared to composite materials or standard steel [12–15], complete reversibility can often be achieved and the isotropy of the stainless steel material may represent a solution for multi-directional loading actions, typical for a structure subjected to static (gravity) and dynamic (earthquake) loads. Furthermore, stainless steel alloys may be readily recycled and are highly durable. Their high ductility and tensile strength are important characteristics when used for structural applications in seismic prone areas, and their attractive appearance and inherent corrosion resistance, even when located in harsh surroundings are additional key features. However, these alloys have not been widely utilized in practice due to a lack of knowledge of their structural behavior and cost limitations.

The objective of this study is to provide the spectrum of the experimental research and practical applications carried out on historic masonry buildings retrofitted using stainless steel profiles. Different successful retrofitting techniques will be described in some detail and applications to important listed monuments will be demonstrated. However, some limitations and constraints still exist, from both the mechanical and practical side. These early successes coupled with others like these, resulted in an expansion of use of stainless steel reinforcement in seismic applications not only for shear walls but numerous other masonry members as well. In this paper we briefly describe some possible future approaches both in terms of new stainless steel materials and innovative retrofitting techniques. These solutions can be viewed as interesting possibilities for the application of stainless steel to reduce the seismic vulnerability of masonry buildings.

2. Stainless steels: Material types

Stainless steels are basically Fe (Iron) alloys with Cr (Chromium) addition as the main alloying element (typically between 10 and 20%), favoring corrosion resistance by means of surface oxidation and protection. Their corrosion resistance is about 200 times higher than that of common carbon steel.