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Review

Strengthening of steel structures with fiber-reinforced polymer composites

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Abstract

Over the past two decades, fiber-reinforced polymer (FRP) composites have gradually gained wide acceptance in civil engineering applications due to their unique advantages including their high strength-to-weight ratio and excellent corrosion resistance. In particular, many possibilities of using FRP in the strengthening and construction of concrete structures have been explored. More recently, the use of FRP to strengthen existing steel structures has received much attention. This paper starts with a critical discussion of the use of FRP in the strengthening of steel structures where the advantages of FRP are appropriately exploited. The paper then provides a critical review and interpretation of existing research on FRP-strengthened steel structures. Topics covered by the review include steel surface preparation for adhesive bonding, selection of a suitable adhesive, bond behavior between FRP and steel and its appropriate modeling, flexural strengthening of steel beams, fatigue strengthening of steel structures, strengthening of thin-walled steel structures against local buckling, and strengthening of hollow or concrete-filled steel tubes through external FRP confinement. The paper concludes with comments on future research needs.

Highlights

► The advantages of FRP composites in strengthening steel structures are highlighted. ► Existing research on the FRP strengthening of steel structures is reviewed. ► Future research needs in the strengthening of steel structures are summarized.

Introduction

Fiber-reinforced polymer (FRP) composites are formed by embedding continuous fibers in a polymeric resin matrix which binds the fibers together. Common fibers used in FRP composites include carbon, glass, aramid and basalt fibers while common resins are epoxy, polyester, and vinyl ester resins. The most widely used FRP composites are glass fiber-reinforced polymer (GFRP) composites and carbon fiber-reinforced polymer (CFRP) composites, while aramid fiber-reinforced polymer (AFRP) composites and basalt fiber-reinforced polymer (BFRP) composites are less frequently used. A useful general background to the composition of these materials and their mechanical properties can be found in Refs. [1], [2], [3], [4]. Fig. 1 shows typical stress–strain responses of FRP composites in contrast with that of mild steel, where it is clearly seen that FRP composites exhibit a linear elastic stress–strain behavior before brittle failure by rupture. This linear–elastic–brittle stress–strain behavior has important implications for the structural use of FRP composites in civil engineering applications.

FRP composites possess several advantages over steel, the most salient of which are their high strength-to-weight ratio and excellent corrosion resistance. The structural use of FRP in civil infrastructure is generally based on the exploitation of these advantages. In particular, FRP, being a material of high tensile strength, can generally be used to its greatest advantages, when combined with concrete which is strong in compression but poor in tension. Therefore, the use of FRP in concrete structures has been a major focus of existing research [2], [4], [5], [6]. Such applications include the external bonding of FRP to concrete structures for strengthening purposes, concrete structures reinforced or prestressed with FRP, concrete-filled FRP tubes as columns and piles, as well as FRP-concrete hybrid beams/bridge decks. More recently, the use of FRP composites in combination with steel, particularly in the strengthening of steel structures, has received much attention. This paper first examines applications where the use of FRP in the strengthening of steel structures presents significant advantages and then provides a critical review and interpretation of existing research on FRP-strengthened steel structures.

Section snippets

Appropriate use of FRP in the strengthening of steel structures

Since steel is also a material of high elastic modulus and strength, the use of FRP in strengthening steel structures calls for innovative exploitations of the advantages of FRP. The main advantage of FRP over steel in the strengthening of steel structures is its high strength-to-weight ratio, leading to ease and speed of transportation and installation, thus reducing disturbance to services and traffic. Another significant advantage of FRP, which applies only to FRP laminates formed via the…

General

Similar to the structural use of FRP in concrete structures, the structural use of FRP with steel can be classified into two categories: (a) bond-critical applications where the interfacial shear stress transfer function of the adhesive layer that bonds the steel and the FRP together is crucial to the performance of the structure; and (b) contact-critical applications where the FRP and the steel need to remain in contact for effective interfacial normal stress transfer which is crucial to…

Flexural strengthening of steel beams

Similar to an RC beam, a steel beam (or a composite steel-concrete beam) can be strengthened by bonding an FRP (generally CFRP) plate to its tension face (i.e. the soffit if a beam in positive bending is assumed, see Fig.6) [37], [54], [57], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97]. The bonded FRP plate can enhance not only the ultimate load but also the stiffness of the beam (especially when a high modulus CFRP is used) [90], [93], [98], [99]; the latter means that the…

Fatigue strengthening

One of the most important aspects of FRP strengthening of steel structures is its capability to improve their fatigue life [112], [113], [114], [115], [116], [117], [118]. Fatigue strengthening studies have been carried out on beams [92], [94], [119], [120], [121], steel plates[116], [117], [122], [123], [124], [125], [126], steel rods [127] and steel connections [128], [129], [130].

Similar to the behavior of FRP-to-steel joints under static loading, Liu et al. [116], [117] found that the…

Buckling induced by high local stresses

In practice, high stresses in a local zone often arise, due to concentrated loads and the need to introduce discrete supports, openings and other local features. Under local high compressive stresses, local buckling failure is likely to control the thickness of a thin-walled steel structure. Such local buckling failure may be prevented by bonding FRP patches. Local high tensile stresses may also be addressed in the same way.

A practically important problem is the web crippling failure of…

FRP confinement of hollow steel tubes

Hollow steel tubes are used in many structures. Local buckling can occur in these tubular members when they are subjected to axial compression alone or in combination with monotonic/cyclic lateral loading. For example, hollow steel tubes are often used as bridge piers and such bridge piers suffered extensive damage and even collapse during the 1995 Hyogoken-Nanbu earthquake [139]. A typical local buckling mode of circular hollow steel tubes involves the appearance of an outward bulge near the…

FRP confinement of concrete-filled steel tubes

Concrete-filled steel tubes (CFSTs) are widely used as columns in many structural systems. In CFSTs, inward buckling deformations of the steel tube are prevented by the concrete core, but degradation in steel confinement, strength and ductility can result from inelastic outward local buckling. When used as columns subjected to combined axial and lateral loads, the critical regions are the ends of the column where the moments are the largest. Under seismic loading, plastic hinges form at the…

Concluding remarks

External bonding of FRP reinforcement has been clearly established as a promising alternative strengthening technique for steel structures by existing research. As more research is conducted and more reliable design guidelines become available, the technique is also expected to receive increasing acceptance in practice. Based on the discussions presented in this paper, it is recommended that future research should address the following issues with priority.…

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