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Effect of adhesive type on Strengthening-By-Stiffening for shear-deficient thin-walled steel structures

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ABSTRACT

Strengthening-By-Stiffening (SBS) is a novel technique whose purpose is to improve structural strength by stiffening buckling-prone regions in thin-walled steel structures using pultruded composite sections. A proof of concept study showed that SBS can achieve gains in shear strength of up to 56% using glass fiber reinforced polymers (GFRP) sections. This paper presents experimental results showing the effect of adhesive type on the efficiency of SBS for shear-deficient thin-walled steel beams. Specimens strengthened with two adhesive types were tested; a generic type (Type I) that is typically used for FRP-strengthening of concrete structures and a relatively new type (Type II) that is particularly promoted for steel structures. Like most FRP-strengthened structures, a debonding failure mode was observed for SBS specimens strengthened using adhesive Type I. Conversely, specimens strengthened using adhesive Type II did not fail by debonding, but rather by buckling of the smaller (less slender) shear panels. The resulting ductile failure mode is uncommon for FRP strengthening techniques and can lead to new applications of FRP strengthening for steel structures that were not possible using more brittle adhesives with lower capacity to absorb inelastic energy.

1. Introduction

Aging steel structures suffer from inadequate capacity due to several reasons such as deterioration because of environmental attacks, increase in applied loads, among others. Extending the service life of existing structures is an economically feasible decision in comparison to full replacement of the structure provided that its strength can be increased to meet applied demands. Therefore, engineers are always exploring new strengthening techniques and materials that are sound, both structurally and economically.

Several methods can be used for strengthening deficient structures including member enlargement, external post-tensioning, and anchoring or welding of additional steel plates. In recent years, the use of adhesively bonded composite materials gained acceptance for strengthening applications because of the many advantages they offer [1]. Composite materials are light weight and can exhibit high tensile resistance, which leads to a high strength-to-weight ratio in comparison to other materials. Additionally, composite materials are not susceptible to corrosion and can be easily handled and installed using adhesives, which allows for minimizing down times of the strengthened structure. Carbon, glass, and aramid fiber reinforced polymers (FRP) have been used in structural strengthening applications. It has been demonstrated that thin carbon FRP (CFRP) sheets, strips or laminates are efficient in strengthening concrete structures because of their high tensile strength [2]. Glass FRP (GFRP) has also been used in strengthening applications. However, the GFRP's lower modulus of elasticity in comparison to CFRP reduces its strengthening efficiency since the main contribution of FRP in strengthening applications is an added tensile capacity in deficient zones. Similarly, the strengthening efficiency of steel structures using CFRP was lower than that of concrete structures because of the higher modulus of elasticity of steel, which leads to the need for large amounts of CFRP to achieve similar strengthening levels as those achieved for concrete structures [3]. Alternatively, the more expensive high or ultra-high modulus CFRP can also be used to strengthen steel structures [4].

Strengthening-By-Stiffening (SBS) is a new effective strengthening method that is suitable for thin-walled steel structures where pultruded FRP composite sections are bonded to buckling prone slender plates [5]. In SBS, buckling resistance of the thin-walled steel members is enhanced by using the out-of-plane stiffness of FRP sections as opposed to conventional strengthening techniques using composite materials that rely on in-plane strength of FRP fibers. This method mimics conventional welded steel stiffeners where the pultruded FRP section corresponds to the steel plate and epoxy bonding corresponds to the welding [6].

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Nomenclature

C_V	coefficient of variation
E_k	elastic modulus of adhesives
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
SBS	Strengthening-By-Stiffening
μ	mean value
σ	standard deviation
ε_u	rupture strain of adhesives
σ_u	rupture stress of adhesives

A schematic illustrating the main components of an SBS strengthened plates; i.e. steel plate, epoxy, and pultruded FRP composite section, can be seen in Fig. 1.

Preliminary experimental results using commercially available materials proved that the SBS concept is an efficient strengthening technique that is highly dependent on the stiffness contribution of the pultruded FRP section and to a lesser extent on the strength of the FRP fibers for structures that are prone to buckling failures [6]. The previous experimental results also showed that the mechanical properties of the adhesive used to bond the pultruded FRP section to the steel plate is the most important factor affecting SBS efficiency since the mode of failure is usually controlled by debonding. While ductile adhesives exist and have been used in other engineering fields, epoxy resins that are commonly used in structural strengthening applications fail in brittle manner [1,7,8]. Several researchers tested plain epoxy specimens under tension, shear and compression loading at different strain rates and temperatures [9–11]. It was reported that specimens fail in brittle manner under tension; however, more ductile behavior was observed for the specimens tested in compression and shear. In general, shear tests exhibited a higher ductile behavior than that observed in tension tests [9]. Furthermore, tension specimens fail at smaller strain levels than the shear and compression specimens [10]. Elevated temperatures were also found to decrease the failure stress of tension specimens [11,12]. Gilat et al. [9] investigated the effect of strain rate on the behavior of plain epoxy tension specimens, and concluded that a ductile response was observed at low strain rates, while a brittle response was observed at medium and high strain rates. Adding rubber particles to an epoxy mix was found to increase the deformation capacity before the failure [13]. Imanaka et al. [14] introduced liquid rubber and cross linked rubber particles to an epoxy mix to enhance its toughness. Another additive was investigated by Zavareh and Vahdat [15] who included bitumen in the epoxy mix, which resulted in an increase in the toughness without changing the other mechanical properties. Saldanha et al. [16] tested new epoxy types with enhanced deformation capacity and toughness without the need for including additional particles. The results show that new epoxies can achieve desired deformation before fracture. Yu et al. [17] studied both linear (brittle) and nonlinear (ductile) adhesives to characterize their bond slip model considering the adhesive thicknesses and axial strength of CFRP laminates when bonded to steel elements. The experimental tests revealed approximately triangular and trapezoidal bond slip models for brittle and ductile adhesives, respectively. Fernando et al. [18] evaluated the interfacial fracture energy between CFRP and steel surfaces bonded using ductile nonlinear adhesives and confirmed the trapezoidal bond slip behavior exhibited by ductile adhesives.

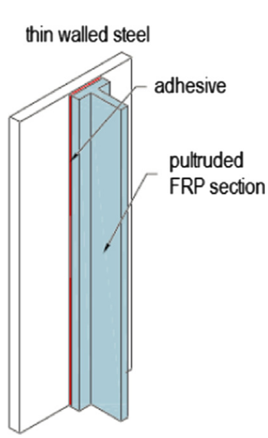

Fig. 1. Schematic representation of SBS method.

It can be seen from the work cited earlier that improving the mechanical properties of epoxy adhesives has gained interest in recent years. Traditional brittle adhesives impose limitations on the efficiency of a very successful structural strengthening technique; i.e., external bonding of FRP composites. The limitation is due to the fact that such strengthening techniques are for the most part controlled by debonding. Therefore, improving the properties of the adhesive translates into improved structural behavior at the member level.

In this paper, SBS is chosen to study the effects of using different adhesive types on the efficiency structural strengthening. First, the mechanical properties of two adhesives were investigated. Both adhesives are then used for stiffening built-up steel beam specimen to enhance their shear capacity. Results from both experimental programs are presented and discussed.

2. Experimental program

An experimental program was first devised to determine the mechanical properties of two commercially available epoxy adhesives and how they affect the shear capacity of steel beams. Tensile coupons of cured epoxy specimens were first tested to determine the stress strain behavior of two adhesive types employed in the strengthening of steel beams. The purpose of conducting these experiments was to explore the behavior of steel beams strengthened using the SBS technique and the effect of different adhesive types on its efficiency. Thin-walled I-shaped steel beams were then tested with and without externally bonded GFRP stiffeners to the critical web panel under shear loading. Furthermore, two web thicknesses were considered to study the effect of initial web slenderness on the efficiency of SBS.

The following sections present the experimental program in more detail:

2.1. Epoxy adhesives considered in this study

As stated earlier, two types of adhesives were investigated. These were: (1) Tyfo® S Saturant Epoxy (Type I) and (2) Tyfo® MB-3 High Performance Adhesive (Type II). Both adhesives are produced by Fyfe Co. and come in two mixable components. For Type I, the final mixture of these components has a relatively lower viscosity around 600–700 cps, and its working time can be 3–6 h. Depending on the surface orientation and required thickness, the viscosity of Type I may be increased by adding fumed silica [19]. Type II is also supplied from the same manufacturer