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Performance of thin-walled steel beams strengthened with GFRP stiffeners bonded using two different adhesives

A. Okeil[1] , T. Ulger[2] and H. Babaizadeh[3]

ABSTRACT

Stiffening buckling-prone regions in thin-walled steel structures using pultruded composite sections is a proven concept developed at Louisiana State University and named strengthening by stiffening (SBS). Experimental studies showed that SBS can achieve gains in shear strength of up to 56% using glass fiber reinforced polymer (GFRP) sections. The effect of different adhesive types on shear deficient thin walled steel structures was investigated with series of experimental studies. Results from tensile tests of epoxy coupons and shear tests of beam specimens strengthened with GFRP stiffeners bonded using two adhesive types are presented in this paper. A generic type epoxy (Type I), which is widely used for FRP-strengthening of concrete structures and a relatively new type epoxy (Type II) that is particularly promoted for steel structures were selected as a bonding material. Epoxy coupons of adhesive Type I failed in tension after undergoing limited elongations, and debonding failure was the only observed failure mode for the SBS beam tests using adhesive Type I. Conversely, Type II epoxy coupons exhibited higher elongation than Type I epoxy coupons before rupture, and beam specimens using adhesive Type II did not fail by debonding, but rather by buckling of the smaller (less slender) shear panels up to the failure.

Keywords: Adhesive, strengthening, steel, shear, buckling, composites

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[1]Assoc Prof., Dept. of Civil & Env. Engineering, Louisiana State University, Baton Rouge, LA,70808
[2]Grad. Res. Assistant, Dept. of Civil & Env. Engineering, Louisiana State University, Baton Rouge, LA,70808
[3]Structural. Proj. Engineer, Stantec Inc., Baton Rouge, LA

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ABSTRACT

Stiffening buckling-prone regions in thin-walled steel structures using pultruded composite sections is a proven concept developed at Louisiana State University and named strengthening by stiffening (SBS). Experimental studies showed that SBS can achieve gains in shear strength of up to 56% using glass fiber reinforced polymer (GFRP) sections. The effect of different adhesive types on shear deficient thin walled steel structures was investigated with series of experimental studies. Results from tensile tests of epoxy coupons and shear tests of beam specimens strengthened with GFRP stiffeners bonded using two adhesive types are presented in this paper. A generic type epoxy (Type I), which is widely used for FRP-strengthening of concrete structures and a relatively new type epoxy (Type II) that is particularly promoted for steel structures were selected as a bonding material. Epoxy coupons of adhesive Type I failed in tension after undergoing limited elongations, and debonding failure was the only observed failure mode for the SBS beam tests using adhesive Type I. Conversely, Type II epoxy coupons exhibited higher elongation than Type I epoxy coupons before rupture, and beam specimens using adhesive Type II did not fail by debonding, but rather by buckling of the smaller (less slender) shear panels up to the failure.

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Introduction

Replacement of deteriorated structures is not always an economically feasible alternative due to the fact that it requires large capital investments. Furthermore, full replacement of deteriorated structures causes disruption to operation and may also affect surrounding activities. Therefore, researchers and engineers are always investigating economical and efficient ways to extend the service life of deteriorating structures by strengthening techniques. Several conventional techniques such as external post-tensioning, anchoring or welding steel plates are available and used for stiffening applications. Alternatively, composite materials, which offer light weight, high tensile strength, and corrosion resistance, have also become acceptable for repairing the deteriorated structures. Polymer based composites made of carbon, glass or aramid fibers have been commonly used in structural strengthening. High tensile resistance of carbon fiber reinforced polymers (CFRP) strips and laminate perform well in strengthening concrete structures [1]. Glass fiber reinforced polymers (GFRP) is another composite material used for strengthening but its modulus of elasticity is lower than CFRP, and the required amount of GFRP is typically higher than the amount of CFRP to achieve the same level of strength. Similarly, strengthening the deficient steel structures using CFRP is not as efficient as strengthening the deficient concrete structures because steel's superior elastic properties requires more CFRP layers to increase the flexural capacity [2].

[1]Assoc Prof., Dept. of Civil & Env. Engineering, Louisiana State University, Baton Rouge, LA,70808
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A new external strengthening method for thin-walled steel structures is a promising application where pultruded FRP composite sections are bonded to shear deficient thin-walled steel panels. This technique is called Strengthening-By-Stiffening (SBS) [3]. Conventionally, external strengthening techniques rely on in-plane resistance of FRP fibers. In SBS, externally bonded composite FRP sections contribute to out-of-plane resistance of deficient thin walled sections, hence, enhancing the shear buckling resistance of overall system. SBS acts simply like a typical welded steel stiffener, where adhesive and composite section are substituted for weld and steel stiffener, respectively [4], and a simple illustration of SBS is shown in Fig. 1.

Experimental results show that SBS is an effective external strengthening technique using pultruded FRP composite sections and adhesives. Brittle behavior is common failure for adhesives that are used in external strengthening applications [5]. The critical failure mode of the tested specimens is the debonding at the interface of steel and FRP section [6]; therefore, mechanical properties of adhesives are important and have been investigated for their tension shear and compression resistance at different temperatures and strain rates [7-9]. Gilat et al. [7] have reported that brittle failure observed at tension, and more ductile behavior observed in compression and shear tests. Likewise, strain levels at failure of the tension specimens is lower than the compression and shear specimens [8]. Plain epoxy coupons tested at small, moderate, and high strain rates, and ductile behavior was observed at small strain rates and brittle behavior was observed at moderate and high strain rates [7]. Littell et al. [9] and Deb et al. [10] also concluded that failure stress will be lower at elevated temperatures. Dean et al. [11], Imanaka et al. [12], and Zavareh et al. [13] showed that additives, such as rubber particles, increased the toughness and deformation capacity of neat epoxy coupons. Saldanha et al. [14] tested a new adhesive and obtained similar increased ductile performance without additives.

The aforementioned studies show that researchers have been investigating the existence of ductile epoxies that exhibits higher elongation and enhanced toughness before rupture. Traditional adhesives used for external strengthening usually fail in brittle manner which limits the overall performance of the structures. The main limitation is the fact that the failure mechanism of strengthening techniques using brittle adhesives is controlled by debonding. Therefore, improved structural performance may be obtained if more ductile adhesives were used instead. In this paper, two different types of epoxy adhesives are considered, and their uniaxial tensile properties are investigated in this paper. The studied adhesives were then used to bond the composite FRP sections to the thin-walled steel beams. Results from coupon and beam tests are presented and discussed in details.

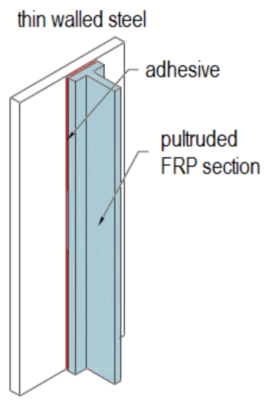


Fig. 1 Schematic representation of SBS method

Experimental Program

Epoxy coupons were cut from mix batches used in subsequent application of GFRP stiffeners for the beam specimens. The coupons were tested to determine the mechanical properties in tension. Built-up I beams were manufactured and tested without FRP strengthening and with FRP strengthening by using two different epoxies.

Epoxy Adhesives

Two commercially available adhesives were considered in this program and named Type I and Type II. Type I, Tyfo® S Saturant Epoxy, and Type II, Tyfo® MB-3 High Performance Adhesive, are products of Fyfe Co. Both adhesives consist of two components that need to be mixed before application. The mixed components of Type I has between 600-700 cps viscosity, which can be adjusted by adding fumed silica in order to obtain desired workable adhesive properties [15]. Type II adhesive's viscosity is around 55000 cps which is significantly higher than Type I, therefore it is noted that working with Type II is more difficult than with Type I [16]. However, the adhesion performance and higher viscosity of Type II facilitates the bonding of FRP sections in vertical and upside down horizontal applications.

Epoxy Preparations and Testing

Type I and Type II epoxies consist of two components, namely Component A and Component B. These two components are mixed using given volumetric ratios (100 A: 42 B for Type I and 100 A: 29.4 B for Type II) following manufacturer's instructions. The final mixtures are obtained by mixing the two components for at least 5 min in room temperature with a mixer attached drill.

ASTM D638, Standard Test Method for Tensile Properties of Plastics, [17] was followed to setup uniaxial test procedure. Both epoxy types were formed in bulk rectangular epoxy plates (254 mm [10in] x 381 mm [15in]. These plates were cut by hydrocut waterjet machine to obtain the dumbbell-shaped coupons. The coupon test setup showing one ruptured specimen and the extensometer position between the hydraulic grips of the MTS universal testing machine can be seen in Fig. 2 (left). Epoxy coupons before and after uniaxial tension tests are shown in Fig. 2 (right).

Fig. 2 Uniaxial tension test setup and epoxy coupons before and after the tension test

Beam Specimens

The main focus of this paper is the effectiveness of the selected epoxy types when steel I-beams are stiffened using both epoxies. In addition to plain epoxy coupons, steel beams were fabricated to form the I-shaped section shown in Fig. 3. The web plates were transversely stiffened as shown to obtain equally spaced panels along the total span. The ratio between the width of the equally spaced panels and the web height is selected to be 1.5, and total span included three panels with a total length of 2438mm (8 feet). Top and bottom flanges, and transverse stiffeners were intentionally over designed to ensure that they do not control the failure mode. Consequently, the failure mode was controlled by shear buckling in the critical web panel. Experimental tests were conducted in three-point load configuration and load point is shown with downward arrow in Fig. 3. The retrofitted steel beams are listed in Table 1. Beams are labeled as BS with the web thicknesses, BS1/8 and BS5/32, and epoxy types are listed as E0, E1 and E2 in Table 1. E0 stands for without stiffening, and E1 and E2 stand for stiffened beam using Type I and Type II epoxies, respectively. For example, the beam which has 3.2 mm [1/8inch] web thickness and is stiffened using Type II adhesive is represented as BS1/8-E2 in following sections.

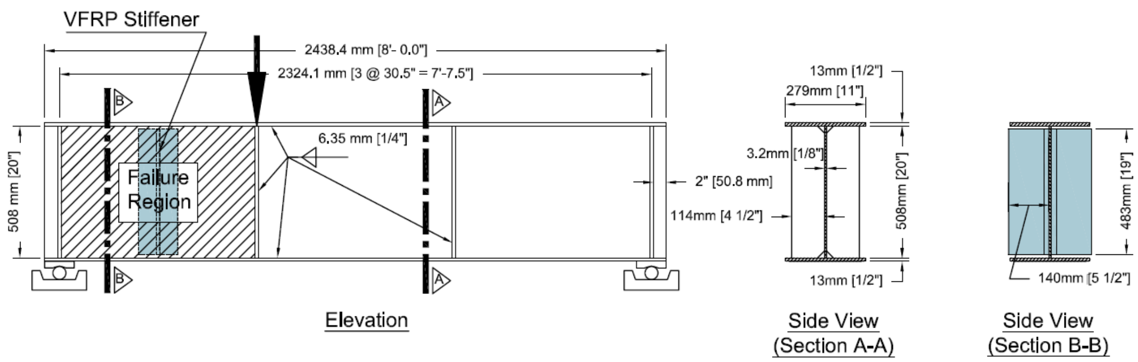


Fig. 3 Built-up I shape steel beams

Table 1 Beams tested with Type I and Type II Adhesives

Beam labels		Web thickness of steel mm[in]	Adhesive
BS1/8	E0	3.2 [1/8]	No FRP
	E1		Type I
	E2		Type II
BS5/32	E0	4.0 [5/32]	No FRP
	E1		Type I
	E2		Type II

Surface Preparations and Testing

Commercial pultruded wide flange GFRP sections were used to stiffen the critical steel web panel. One flange of the pultruded GFRP sections was cut to create T-shaped sections. These T sections were bonded vertically to the steel surface using two epoxy types. In an earlier study, one T section was bonded diagonally to the steel web to evaluate the behavior of externally retrofitted beams. Vertical orientation was the main consideration of the proposed strengthening method due to exceptional ductile performance over the diagonal orientation. More details on the orientation of GFRP sections can be found elsewhere [18].

Surface preparation of the pultruded GFRP and steel sections is the most critical process for externally bonding applications. There is not any specifically defined surface preparation procedure for pultruded GFRP sections in literature; therefore, artificial surface roughness and removing any residual particles from the surface were the general approach for preparing the surface of GFRP sections. All pultruded sections are fabricated with some kind glazed finishing which does not contribute to the surface roughness and friction energy. The outer glazed finish of the T section's flange was randomly with a sharp object, and the resulting roughened surface was cleaned using acetone before bonding. Steel surface preparation was described by Baldan [19] and Schnerch et al. [20], and similar steel surface preparations are listed; (1) Steel surfaces are freed from any type contaminants such as, rust, mud, grease or oil. The bulk contaminants may be removed with a metal scraper, and the fine residues may be cleaned with towels, if necessary, softening with some chemicals, such as acetone. The surface needs to be dried before the next step. (2) The second step removes the barrier paint and very thin layer of metal from the surface using sand papers and poly abrasive wheel attached to drill. (3) Due to abrasive action on the surface, remaining fine particles were wiped using acetone right before the bonding. The goal here is to reach the white metallic surface without any interruption of paint and fine particles; therefore, perfect bond between the epoxy and steel was achieved.

Once pultruded GFRP section and steel were purely cleaned, Type I or Type II adhesive applied on both surfaces separately. GFRP T sections were oriented vertically and bonded to center line of the steel web panel. The air and voids inside the epoxy layers were removed by applying small force onto the T section. Also the epoxy layer between the steel and T section was minimized to reduce the stress concentrations in epoxy layer. The thickness range of the epoxy layer was from 2.5 to 3.5mm in testing environment. Although the resultant thicknesses quite larger than the expected epoxy layer, the similar thickness variations will most likely be exist in real structures due to the initial imperfections. The residual epoxy film due to applied force on the left and right side of the T sections cleaned before complete curing; therefore the epoxy film resistance was not accounted in shear resistance.

Experimental Results

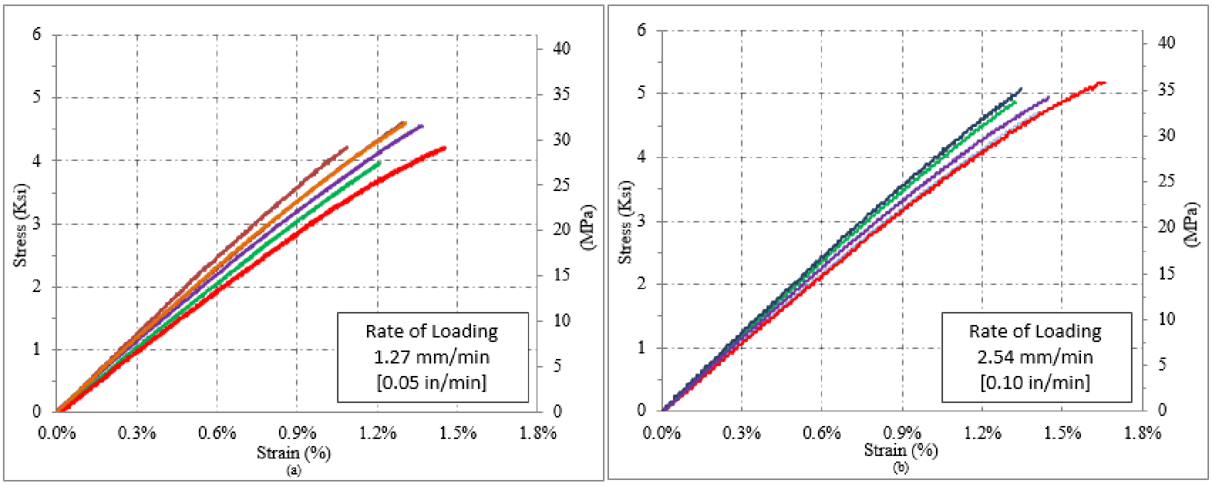
Epoxy Tests

Axial tension tests were conducted for each epoxy coupons. The ASTM D638-03 test procedures was followed to determine the stress-strain relationship for both epoxy types. According the ASTM D638-03 standard, each specimen should fail within a test duration between 0.5 and 5 minutes. After several trials, displacement rates that satisfied the specified range were determined. Two different displacement rates were considered in each epoxy group to obtain elastic modulus, rupture stress and maximum strain at rupture. The displacement rates were 1.27 mm/min [0.05 in/min] and 2.54 mm/min [0.10 in/min] for Type I coupons, and 0.635 mm/min [0.025 in/min] and 1.27 mm/min [0.05 in/min] for Type II coupons. Tensional properties of Type I and Type II epoxies are given in Table 2 and Table 3, respectively.

The rate of loading increases the rupture stress for both epoxy types. The averaged rupture stress of Type I and Type II epoxy coupons are around 30 and 12 MPa, respectively. The obtained values when compared to the steel and concrete materials are low [21]. However, the elongation ability at rupture are considerably high, especially for Type II epoxy coupons.

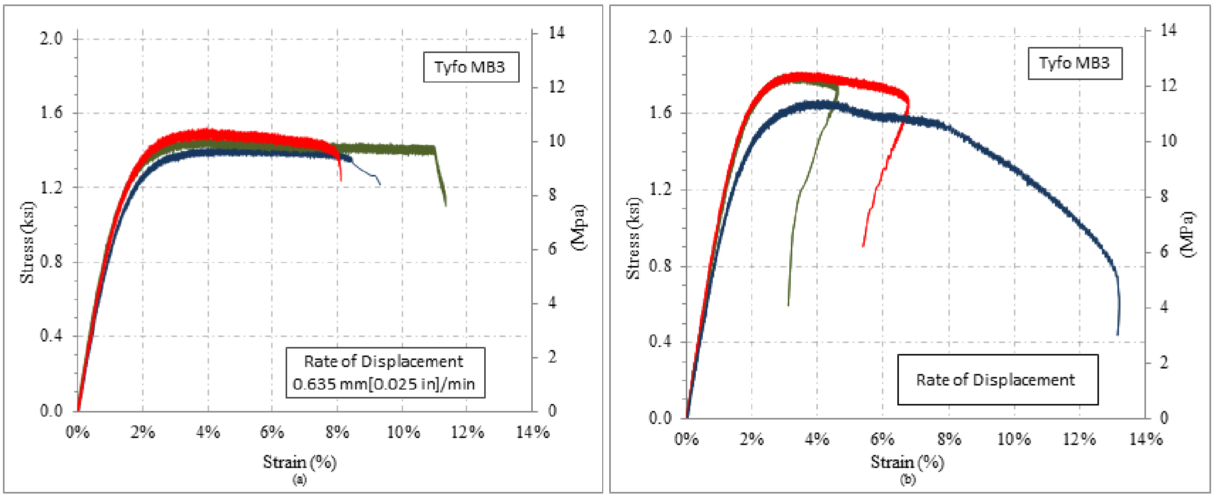
There was not any consistent relation observed between the displacement rate and rupture strain for Type II epoxy coupons. The stress-strain curves of Type I and Type II epoxies are plotted in Fig. 4a and Fig. 4b. The maximum elongations of Type I coupons did not exceed the 1.5% for both displacements rates.

Unlike Type I epoxy coupons the overall behavior of Type II epoxy coupons are quite different as can be seen in Fig. 5a and Fig. 5b. One major distinct behavior of Type II epoxy coupons is the higher variance of its elongation ability from 4 to 13%. The variance in the rupture strains were not as high when compared to the rupture strains of Type I epoxy coupons. Nevertheless, the ductile behavior is not common for most adhesives used in structural applications. Therefore, this uncommon elongation ability of Type II epoxy has positive performance effect on SBS technique. Such ductile adhesives can perform well in high stress concentrated regions and may alter the possible failure modes.



(a) 1.27 mm/min [0.05 in/min] strain rate (b) 2.54 mm/min [0.10 in/min] strain rate

Fig. 4 Stress-strain curves of Type I



(a) 0.635 mm/min [0.025 in/min] strain rate (b) 1.27 mm/min [0.05 in/min] strain rate

Fig. 5 Stress-strain curves of Type II

Beam Tests

The effect of different adhesives on SBS was experimentally investigated. The load-deflection curves of these beams are shown in Fig. 6. The control specimens, BS1/8-E0 and BS5/32-E0, reached a load resistance of 222 kN [50 kips] and 294 kN [66 kips], respectively. The post yielding behavior of both beams was linear at a constant resistance; i.e., without losing its load resistance. This is due to the elements surrounding the critical panel (vertical stiffeners and horizontal flanges) engaging in a sway-frame mechanism to resist the applied loads after the buckling of the web.

Table 2 Mechanical properties for Adhesive Type I

	Rate of Loading					
	1.27 mm/min [0.05 in/min]			2.54 mm/min [0.10 in/min]		
Six Specimens	Elastic Modulus E_k, MPa [ksi]	Rupture Stress σ_u, MPa [ksi]	Rupture Strain ε_u (mm/mm)	Elastic Modulus E_k, MPa [ksi]	Rupture Stress σ_u, MPa [ksi]	Rupture Strain ε_u (mm/mm)
μ (mean)	2575 [373.47]	30.13 [4.37]	0.0129	2642 [383.15]	33.37 [4.84]	0.0141
σ (SD)	202 [29.32]	1.72 [0.25]	0.0012	126 [18.24]	2.07 [0.30]	0.0013
C_V (%)	7.85%	5.66%	8.99%	4.76%	6.30%	9.30%

Table 3 Mechanical Properties for Adhesive Type II

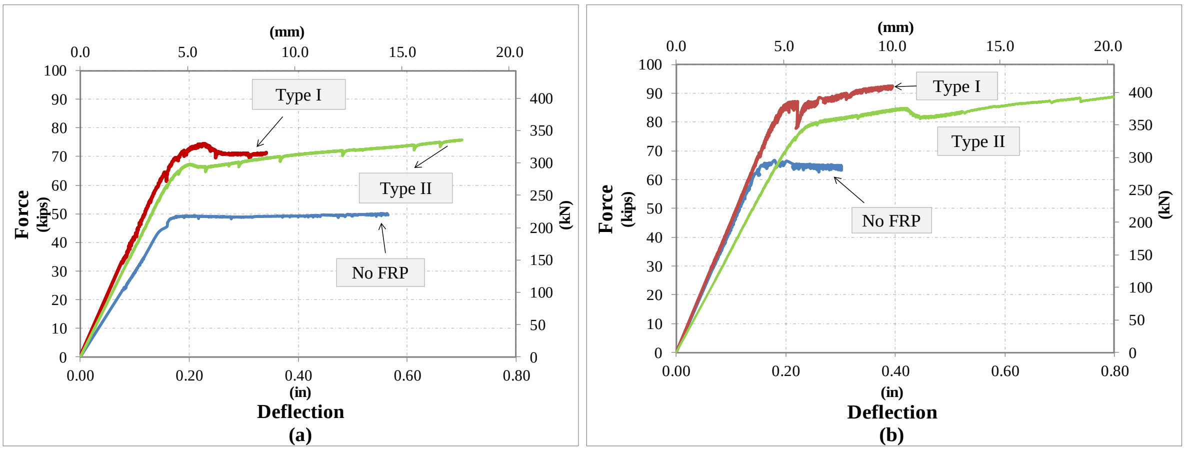
	Rate of Loading					
	0.635 mm/min [0.025 in/min]			1.270 mm/min [0.05 in/min]		
Three Specimens	Elastic Modulus E_k, MPa [ksi]	Rupture Stress σ_u, MPa [ksi]	Rupture Strain ε_u (mm/mm)	Elastic Modulus E_k, MPa [ksi]	Rupture Stress σ_u, MPa [ksi]	Rupture Strain ε_u (mm/mm)
μ (mean)	649 [94.10]	10.1 [1.47]	0.0982	708 [102.65]	12.20 [1.77]	0.0820
σ (SD)	31 [4.47]	0.27 [0.04]	0.0132	41 [5.93]	0.50 [0.07]	0.0366
C_V (%)	4.75%	2.88%	13.47%	5.78%	3.80%	44.60%

The load-deflection curve for the more slender beam, BS1/8, is plotted in Fig. 6a. Similar to the Type II epoxy coupons BS1/8-E2 beam exhibit plastic deformation ability, and the load capacity was slightly increased up before the failure. The failure of the Type I stiffened beams was obvious with cracking sounds in early stage of post buckling, but there was not any audible signs until the last stage of post buckling with Type II stiffened beams. The ultimate load carrying capacity at failure was increased 36 and 51% using Type I and Type II epoxies, respectively. Table 4 lists the results from all beam tests. The initial stiffnesses of the stiffened beams were increased slightly for BS1/8 beams, but the increase is not as much as the strength increases.

The behavior of the less slender beam specimens, BS5/32, are plotted in Fig. 6b. It can be seen that Type I stiffened beam, BS5/32-E1, had a higher initial yield load than Type II stiffened beam, BS5/32-E2. However, an early sudden load drop was observed when the BS5/32-E1 was loaded, and this drop followed by a gain in load carrying capacity as can be seen in Fig. 6b. The strength gains of the stiffened beams were 40 and 39% for the Type I and Type II stiffened beams, respectively, and their ultimate failure loads are summarized in Table 4. The initial stiffness result of Type II stiffened beam, BS5/32-E2, did not reflect a conclusive result. The expected behavior falls between the Type I stiffened and non-stiffened case as occurred in BS1/8 beams. More testing using both epoxies is needed to better understand the unexpected behavior as observed in stiffness loss of BS5/32-E2.

Table 4 Load carrying capacities with/without FRP stiffeners

Beam Labels		SBS	Failure Load kN[kips]	Capacity Increase
BS1/8	E0	No FRP	222 [50.0]	--
	E1	Type I	302 [68.0]	36%
	E2	Type II	336 [75.5]	51%
BS5/32	E0	No FRP	294 [66.0]	--
	E1	Type I	411 [92.5]	40%
	E2	Type II	409 [92.0]	39%



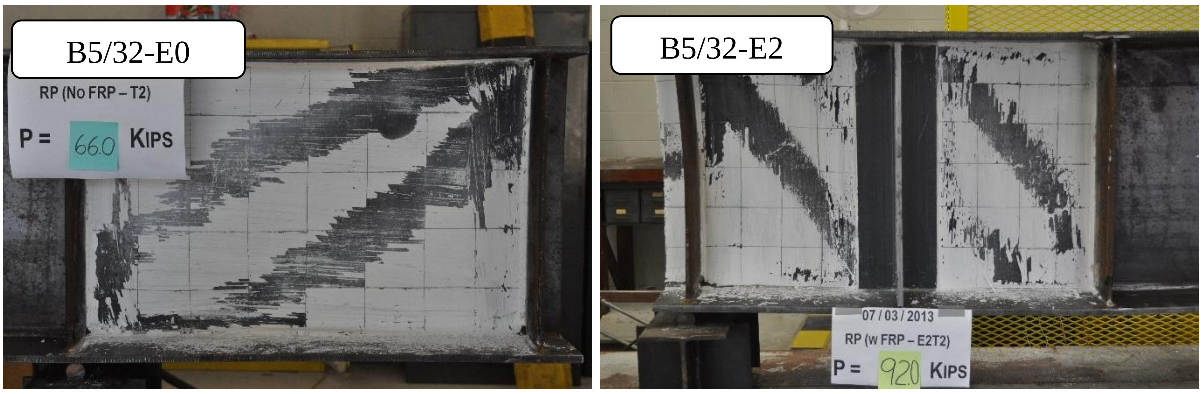
(a) BS1/8 (web thickness = 3.2 mm) (b) BS5/32 (web thickness = 4.0 mm)

Fig. 6 Load Deflection Curves for Beam Specimens

The failure mechanism of unstiffened beam can be depicted as a single buckling wave towards the outer plane over the diagonal line, and one example of this typical buckled shape can be seen in Fig. 7a. On the other side the failure of the stiffened beams did not follow one single diagonal path as observed in unstiffened beams' failure. Typically, two similar but shorter diagonals observed in the stiffened beams as shown in Fig. 7b. The first initial diagonal failure starts between the bearing and GFRP stiffener, and the second one starts between the GFRP and first steel transverse stiffener, or the other way around. At the final stage, two diagonal failure lines became a continuous failure line. The GFRP stiffened beams using Type I adhesive debonded with cracking noises and revealed excessive deformations; however, the failure of Type II adhesives revealed excessive deformations followed by debonding.

Conclusions

The new retrofitting method of thin-walled steel structures, SBS, was explored further in this research using two different adhesives. Uniaxial tension tests were conducted using dumbbell shaped plain epoxy coupons to first identify behavior of both epoxies. Type I epoxy coupons failed in brittle manner with lesser elongation; however, Type II epoxy coupons revealed higher elongation before failure. Type II coupons have an apparent yield-like behavior with a plateau similar to that common for steel. Similar to the epoxy coupons, the steel beams stiffened using Type I epoxy failed with sudden load drops, but gradual load increases were observed without load drops when Type II was used. The load carrying capacity of the GFRP stiffened steel beams was increased up to 51% over the unstiffened beams. The failure of steel web panel was altered with the proposed retrofitting method. The retrofitted web panels' failure initiated in one side of the GFRP section and propagated to the other in opposed to the unstiffened web panel. Slight increase in initial stiffnesses of the retrofitted beam was expected and observed clearly in thinner steel web panel which has 3.2mm [1/8inch] web thickness. The behavior of the new strengthening technique using the considered adhesive types convinced the authors that SBS is an effective retrofitting technique, and the performance of this proposed method can be enhanced with the use of new ductile epoxies as they emerge for structural applications.



(a) BS5/32 –E0 (unstiffened) (b) BS5/32-E2 (Type II adhesive)

Fig. 7 The Failure mode of tested beams

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