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# Effect of initial panel slenderness on efficiency of Strengthening-By-Stiffening using FRP for shear deficient steel beams

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ABSTRACT

The need for strengthening steel structures is as important as it is for concrete structures, or any other aging structure. Strengthening concrete structures by externally bonding thin composite materials in the form of laminates or strips has proven to be an efficient way for enhancing the flexural, shear, and axial strength of deficient elements. Use of external bonding of thin composite material to strengthen steel structures can also be found in literature. This paper presents another effective strengthening technique in which pultruded GFRP sections are bonded to shear deficient regions to enhance the local buckling resistance of thin walled steel structures. Three steel beams with different web thicknesses were tested experimentally with and without GFRP stiffeners to study the efficiency of the new technique; Strengthening-By-Stiffening or SBS. The ultimate shear capacities of the beams were enhanced by a minimum of 30% when one stiffener was used on a beam with a square panel and a maximum of 40% for beams with larger rectangular panel with two stiffeners (one on each side). The initial global stiffness was also enhanced between 5% and 41% for the strengthened beams as a result of the externally bonding the GFRP stiffeners. Unlike the one stiffener configuration which experienced a major load drop at high load levels, the post yielding behavior of the two stiffener configuration exhibited a sustainable load capacity around the peak load without any major load drop. Strain reading from the top and bottom flanges at the loading point revealed that a sway frame mechanism became the main shear resisting mechanism after the critical panel buckled due to shear.



## 1. Introduction

The high cost of replacing aging structures drives owners to look for more feasible and economical solutions. Therefore, retrofitting existing structures has become the most common and practical solution to enhance the minimum strength and serviceability limits for aging structures. Retrofitting also addresses sustainability by extending the service life of existing structures without the need to invest unavailable larger capital resources for a new structure. Thus, existing structures can be utilized for a longer period, and the need for recycling it is delayed resulting in the use of smaller amounts of materials with lesser carbon footprint [1].

Composite materials such as fiber reinforced polymers (FRP) are well suited for retrofitting concrete structures because of their superior mechanical properties relative to traditional construction materials (e.g. concrete) in addition to being light weight and corrosion resistant. In the United States, ACI 440.2R-08 [2] provides guidance for the design of externally bonded FRP systems for strengthening concrete structures. Several other guidelines and codes have also been published around the world [3–6]. Strengthening steel structures using externally bonded FRP systems is relatively new when compared to traditional strengthening techniques (i.e. steel plate welding and concrete jacketing) and is lagging behind FRP applications for strengthening concrete structures. Advanced manufacturing technologies of FRP systems allow FRP fibers to be woven within a matrix to form various structural shapes such as I-and T-shapes. FRP structural shapes have the advantage of offering out of plane resistance in addition to the typically utilized in-plane resistance of thin FRP products such as sheets and laminates. The out-of-plane resistance of pultruded FRP sections was first used to stiffen thin walled steel beams by Okeil et al. [7] as a pilot study, and the ultimate shear resistance increased by 56% when the pultruded GFRP stiffeners were bonded to the web. The strengthening technique whereby pultruded FRP shapes are used as stiffeners to steel plates in thin-walled beams will be referred to as *Strengthening-By-Stiffening*, or *SBS*.

In this paper, an experimental program to investigate the effect of web slenderness and shear panel's aspect ratio on the efficiency

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**Nomenclature**

| | |
|---|---|
| $L$ | length of the beam |
| $h$ | height of steel web |
| $t_w$ | thickness of steel web |
| $P$ | applied load on the control panel |
| $\Delta$ | vertical displacement at the load line |
| $E_f$ | flexural Modulus of Elasticity |
| $E_a$ | axial Modulus of Elasticity |
| $\sigma_y$ | yield strength |
| $\sigma_u$ | ultimate strength |
| $\varepsilon_u$ | ultimate strain |
| $K_i$ | initial stiffness |
| $\mu$ | sample mean |
| $\sigma$ | standard deviation of a sample |
| $C_v$ | coefficient of variation |

of the SBS technique is first described. Three thin-walled steel beams with two different panel aspect ratios and web thicknesses employing the SBS technique were tested to failure. Results from the conducted tests are then presented, and finally, conclusions are drawn based on the findings from the presented results and discussions.

## 2. Composite strengthening

External bonding of FRP composites is an accepted strengthening technique for concrete structures As is evident by the many successful applications reported in the literature [8,9]. In comparison, traditional strengthening techniques (e.g. post tensioning bolting of additional steel plates) still account for the vast majority of the strengthening jobs of steel structures. The same can be said about research in both strengthening arenas as well. A quick search shows that the published work on FRP strengthening of concrete structures is about three times that of steel structures. Therefore, there is a need to fill the knowledge gaps on the use of FRP for strengthening steel structures before any design guidelines can be established, which is the first step towards acceptance and use in field applications.

Increasing the ultimate load carrying capacity is mainly the primary objective for strengthening applications, which is often accompanied by loss of ductility [7]. A more ductile performance was observed when GFRP (Glass FRP) or KFRP (Kevlar FRP) were used for strengthening reinforced concrete structures [10], however, the required amount of FRP is typically larger than the amount of CFRP (Carbon FRP) [10,11]. Published work shows that the most widely used composite material for strengthening steel structures is the CFRP sheet/strips with some efforts recommending high or ultra-high modulus CFRP for strengthening steel structures [12,13]. This is due to the higher elastic modulus of CFRP as opposed to other types of composites (e.g. GFRP) makes it more compatible with the mechanical properties of steel. For example, the flexural strengthening of the steel sections were studied experimentally and numerically utilizing different forms and layers of CFRP composites on the tension side of the steel girders [11,14–17]. In addition to the flexural strengthening efforts, researchers also investigated the feasibility of using composite materials to strengthen steel structures subjected to axial and shear forces. Different steel joint types (e.g. K and V) subjected to the axial forces were also strengthened by wrapping different number of CFRP composite layers [18–20]. A limited number of experiments investigating shear strengthening of steel structures using composites were conducted bonding different form CFRP composites in different configurations [21,22].

The concept in these conventional techniques is the utilization of in-plane resistance of an external reinforcing material, which quickly revealed that the efficiency is less than that observed in strengthening concrete structures due to the large amount of FRP needed for strengthening steel structures [11,18]. In the proposed SBS technique, a different form of composite materials; pultruded FRP sections, is utilized in an innovative way resulting in a practical strengthening technique while reducing the amount of FRP usage.

## 3. Proposed strengthening technique

The main concept behind the proposed SBS technique is the utilization of pultruded FRP sections to enhance the capacity of shear deficient thin-walled steel structures. Fig. 1 shows an illustration of how a wide-flanged pultruded FRP section can be bonded to a thin, buckling-prone steel plate. The enhancement in shear resistance is caused mainly by delaying buckling of the steel plate as a result of the additional out-of-plane stiffness provided by the pultruded FRP section. Therefore, this stiffening method allows using cheaper, low-modulus fibers within the matrix resins of the composite section to strengthen steel structures whose elastic modulus is inherently higher. SBS success stems from the fact that the flexural rigidity, *EI*, of the additional stiffener is an order of magnitude higher than that of the deficient steel plate. The first preliminary study on using the SBS technique was conducted by Okeil et al. [23], and more technical details can be found elsewhere [7].

## 4. Experimental program

An experimental program was designed to study the effect of initial web slenderness on the efficiency of SBS in enhancing the shear strength of thin-walled steel beams. The program consisted of eight beam specimens with different web thicknesses, shear panel dimensions, and FRP stiffener configuration. Varying the

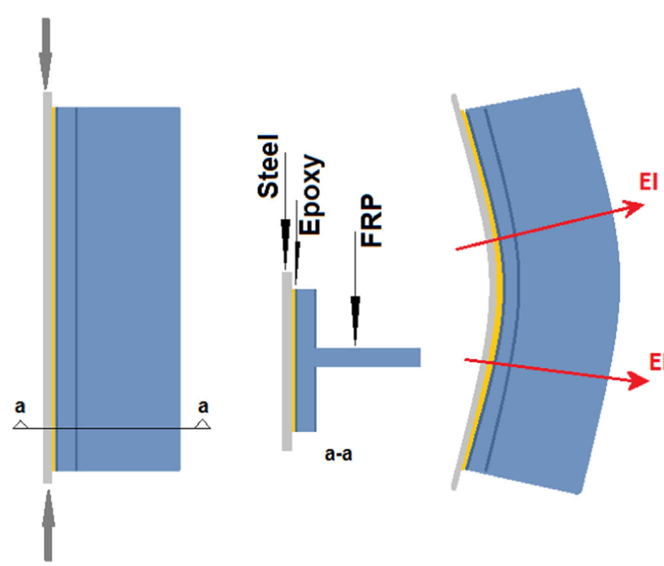


**Fig. 1.** Out-of-plane resistance of pultruded GFRP section (not scaled sketch).