First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Strengthening-By-Stiffening: Analysis Model Validation and Parametric Study

Ayman M. Okeil[1], Gabriel Broussard[2], and M. Rubiat Ferdous[3]

[1] Associate Professor, Department of Civil and Env. Eng., Louisiana State University, Baton Rouge, LA, USA
[2] Fmr. Graduate Student, Department of Civil and Env. Eng., Louisiana State University, Baton Rouge, USA
[3] Fmr. Research Assistant, Department of Civil and Env. Eng., Louisiana State University, Baton Rouge, USA

ABSTRACT: Strengthening-By-Stiffening (SBS) is an innovative technique that has proven success in enhancing the behavior and capacity of deficient thin-walled steel structures. The new promising utilization of FRP pultruded sections to stiffen thin-walled steel sections utilizes large flange area to bond additional stiffeners to slender steel plates using adhesives. The concept was tested experimentally where strength gains of 56% were achieved for shear controlled I-shaped steel beams. The failure mode was controlled by the debonding of the adhesive. This paper presents an analysis model based on the finite element (FE) method. The developed model introduces a new epoxy degeneration algorithm to simulate the debonding observed in the experimental tests. The FE model also accounts for geometrical and material nonlinearities. After validating the results of the model using experimental results, a parametric study was conducted to study the effect of web slenderness and contact area on the efficiency of SBS strengthening. Conclusions are drawn and recommendations for future research are made.

1 INTRODUCTION

Strengthening of existing structures has become a routine activity to upgrade existing deficient structures so that they can meet new higher load demands and overcome deterioration due to natural and man-made events. For example, several agencies (e.g. American Society of Civil Engineers -ASCE) have estimated the number of bridges in need for strengthening to be in the thousands. Full replacement of this large long-term capital investment is the best solution, albeit not fiscally possible. Therefore, many owners consider strengthening as the feasible alternative. This fact is troubling and, combined with the fiscal constraints, has prompted extensive research into strengthening and repair techniques.

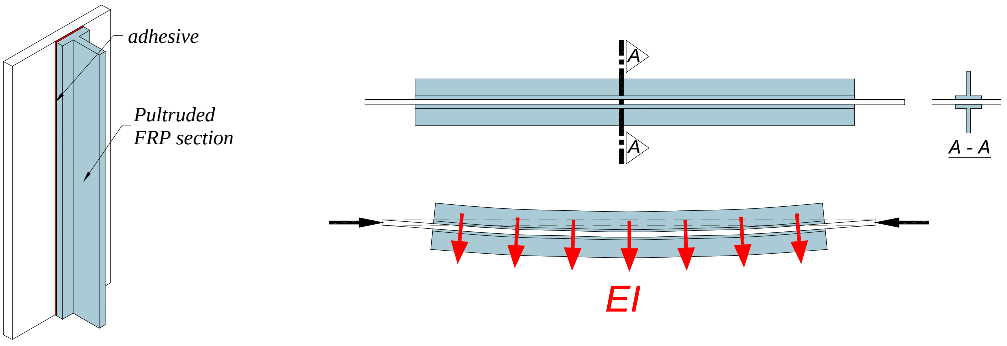
Several strengthening techniques are available nowadays, some of which utilize traditional civil engineering materials such as concrete (jacketing) or steel (external prestressing), while others utilize materials that were recently introduced in civil engineering applications (e.g. fiber reinforced polymer (FRP) composites and shape memory alloys (SMA) smart materials). The use of externally-bonded composite materials for strengthening concrete structures has been gaining acceptance because of the superior qualities they offer to deficient concrete structures.

High tensile strengths, ease of application, and corrosion resistance are just some of the advantages that made composites a popular alternative for structural strengthening of concrete structures. Research on the use of composites in steel strengthening applications has also shown promising potential. One of the earliest investigations in strengthening composite materials was published by Sen et al. (1995). In a later publication, (Sen et al. 2001), it was concluded that to achieve comparable strength and stiffness gain typically obtained in strengthened concrete and wood members (11% to 50%), much thicker Carbon FRP (CFRP) laminates are needed for strengthening steel members. Tavakkolizadeh & Saadatmanesh (2003) showed that gains up to 76% can be achieved for steel-concrete composite girders strengthened using CFRP sheets under static loading. In recent years, the availability of high modulus FRP materials helped demonstrate the potential for new steel strengthening applications (Schnerch et al. 2004). Fawzia et al. (2007) investigated the behavior of very high strength (VHS) circular steel tubes strengthened by CFRP under axial tension. High modulus (HM) CFRP was found to be superior to normal modulus CFRP in retrofitting steel tubes. Shaat and Fam (2006) studied the behavior of axially loaded short and long square hollow structural section (HSS) columns, strengthened with CFRP sheets. Maximum strength gains of 18% and 23% were achieved for short columns and long columns, respectively. More recently, a special issue of the Thin-Walled Structures journal (October 2009) was dedicated to FRP-strengthening of metallic structures and included a few articles enhancing the buckling performance of steel structures using composites. Harries et al. (2009) presented the use of longitudinal strips of CFRP to mitigate local buckling due to bending stresses in a flanged steel section based on an experimental program. Zhao and Al-Mahaidi (2009) also presented an investigation of beams strengthened with CFRP plates for end-bearing forces in light gage steel members with the goal of enhancing the resistance to web crippling.

In FRP strengthening applications of concrete and steel structures, the in-plane qualities of composite materials have been utilized by placing them in zones where additional tensile capacity is needed (e.g. soffit of a simply supported beam). This paper presents an analytical model for investigating a new technique for strengthening thin-walled steel structures that was recently developed by the first author's research team (Okeil et al. 2009). The new technique avoids adverse effects associated with welding steel stiffeners such as stress concentrations and residual stresses that may reduce the fatigue life of the strengthened structure.

2 STRENGTHENING-BY-STIFFENING (SBS)

Figure 1-a shows a schematic of the new strengthening technique developed by the first author's research team. It can be seen from the figure that by utilizing a large contact area between the flange of a pultruded FRP section and the stiffened steel plate, an additional stiffener can be attached to a deficient plate using an adhesive such as epoxy. The impact of adding an FRP stiffener to a thin-walled steel section is similar to that of conventional welded steel stiffeners in that it would reduce the plate's slenderness. Thus, a delay of buckling as well as an improved post-buckling behavior is to be expected. The new strengthening technique relies on adding stiffness to buckling prone plates. It will, therefore, be referred to as *Strengthening By Stiffening (SBS)*. Unlike other FRP strengthening techniques where the ***in-plane strength*** (tensile capacity) of the composite material is the major agent in the strengthening scheme, SBS relies on the ***out-of-plane stiffness*** of the pultruded section as the major contributing factor. Figure 1-b illustrates how SBS restrains the out-of-plane deformation of the strengthened plate that may take place in buckling-prone regions. The in-plane strength of the FRP stiffener may be irrelevant in the proposed strengthening technique with proper orientation of the stiffener.



(a) Pultruded FRP stiffener (b) Out-of-plane contribution

Figure 1. A typical FRP stiffener used in SBS strengthening (Okeil et al. 2009)

A pilot experimental program (Okeil et al. 2010) where three specimens were tested showed the feasibility of utilizing low modulus FRP sections as stiffening components for buckling prone regions in thin-walled steel structures. Web buckling was chosen as the investigated mode of failure of the steel beam, which was achieved by overdesigning all other possible modes of failure. Figure 2 shows the dimensions of the built-up steel specimens used in the pilot investigation. A single point load was applied over the first internal stiffener on one side of the beam causing the first panel to be subjected to 3 times the shear force acting on the rest of the beam. Two FRP stiffener configurations were tested. The GFRP stiffener was positioned vertically in the first specimen (VFRP) and diagonally along the compression strut in the second specimen (DFRP) as can be seen in Figure 2. The gain in buckling load was 56% for the VFRP stiffener configuration and 70% for the DFRP stiffener configuration.

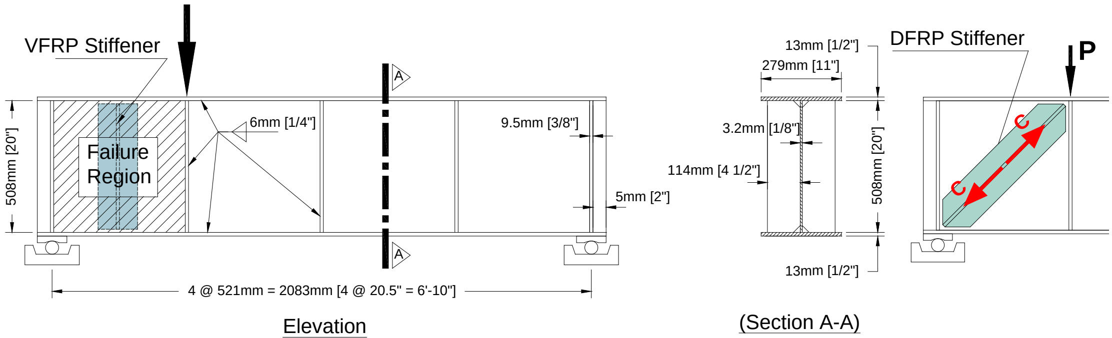


Figure 2. Dimensions of specimens showing VFRP and DFRP configurations.

Figure 3 shows a plot of the normalized load-displacement curves obtained for the control specimen and both stiffened specimens. It can be seen that the gain in strength caused by SBS comes at the expense of the member's ductility. This is typical of FRP strengthening techniques due to the brittle nature of composite materials and the associated debonding failure mode. Both strengthened specimens failed when the epoxy bonding the FRP stiffener to the beam's web failed leading to an immediate loss of the stiffness, and hence, global failure. It should be noted, however, that SBS strengthened beams are not completely brittle. As can be seen in Figure 3, the beams absorbed plastic energy prior to failure, which may be defined as the difference between the total area under the load-displacement relationship and the elastic energy that would be released if unloaded (shaded area in Figure 3). It should be noted that despite the higher strength gain for the DFRP specimen, its lower ductility was seen as an undesirable feature of SBS when the stiffeners are positioned as load bearing members; i.e. compression strut in the case of the DFRP specimen.

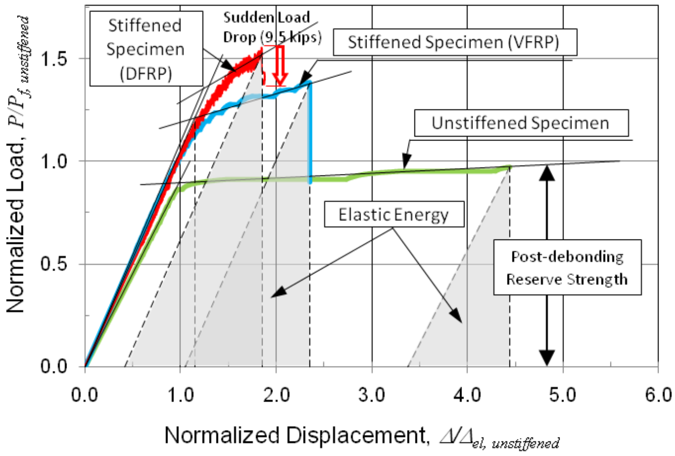


Figure 3. Comparison between the behavior of stiffened (VFRP and DFRP) and unstiffened beam specimens (No FRP). (Okeil et al. 2010)

3 ANALYSIS MODEL AND VALIDATION

3.1 Model Description

A state-of-the-art model was developed to be used in better understanding the effect of key variables on the behavior of FRP stiffened steel structures. The developed model accounts for geometric nonlinearity to capture steel local buckling and post-buckling behavior, as well as material nonlinearities including FRP rupture, steel plasticity, and adhesive debonding. The model was built using 8-node solid elements to model the thin-walled steel members, the FRP stiffeners, and the adhesive layer between both materials. Perfect bond between the epoxy and the steel and FRP elements was assumed. This assumption is based on experimental observations where debonding only occurred after excessive cracking within the epoxy material itself. Preliminary results were obtained from a model using the commercial Finite Element (FE) package ANSYS (2008) for the VFRP specimen tested in the pilot study. The DFRP specimen was not considered in the analytical investigations as the research team now focuses its development of the SBS technique on the more ductile stiffener orientations when they are not positioned to be direct load bearing members such as the case of DFRP specimen. Epoxy and FRP elements were assigned linear elastic material properties. Five coupons from the web, which was manufactured from A36 steel, were tested to determine the actual stress-strain curve. The data from these tests was fitted to define a piece-wise linear stress-strain relationship for steel in ANSYS. Figure 4 shows a plot of the idealized stress-strain relationship used in this study.

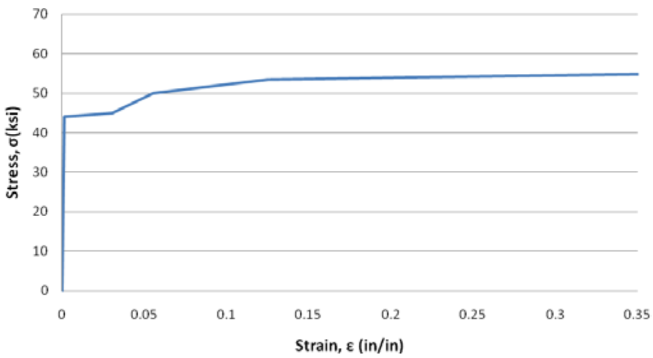
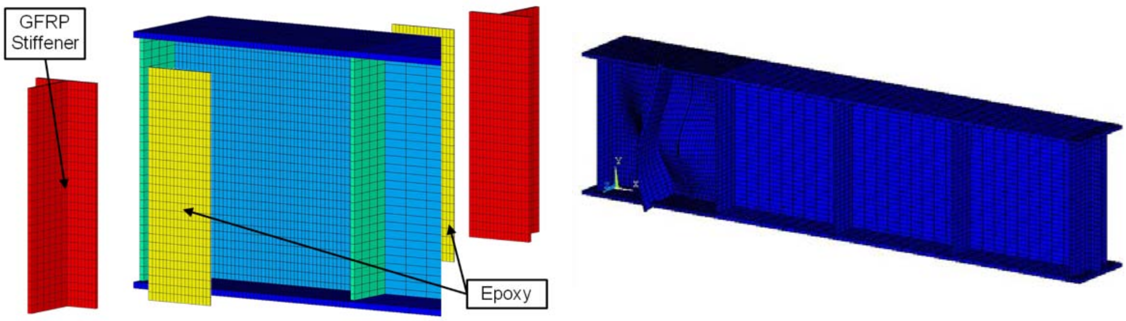


Figure 4: Idealized Stress-Strain Relationship of Steel for Web.

A picture of the critical panel from a completed model can be seen in Figure 5, which was first used to perform an "eigen" analysis of the beam. The results from the eigen analysis were then used to impose an initial distortion to the beam's "perfect" coordinates in the original FE model by superimposing a fraction of the 1st buckling mode shape. A nonlinear finite element (FE) analysis is then conducted using the distorted model in which material as well as geometric nonlinearities were accounted for. A progressive elimination technique of epoxy elements was devised where these elements are removed from the model (*killed*) after each iteration if a prespecified failure criterion is met. The results shown in this paper are based on comparing the Von Mesis equivalent strain to the failure strain of the epoxy material.

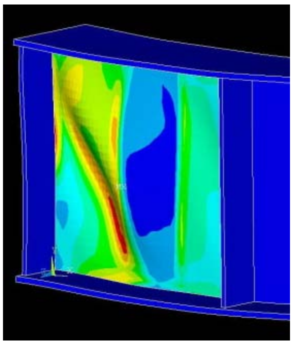


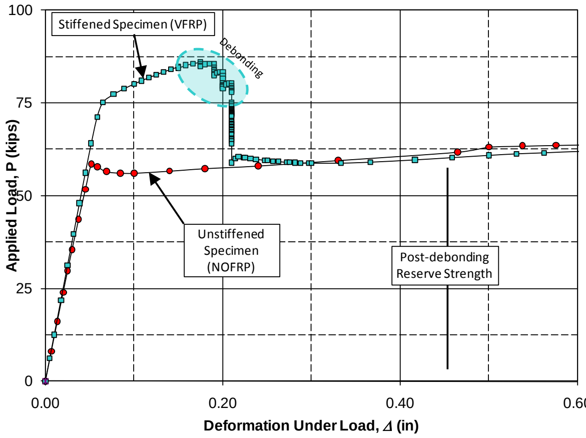
(a) (separating elements by material type for clarity) (b) 1st Buckling mode (initial imperfection)

Figure 5. Proposed FE model.

3.2 Model Validation

The resulting failure mode is shown in Figure 6-a which is similar to the experimentally observed failure mode. It can be said that the developed model is capable of capturing the nonlinear geometric behavior of the specimen. Figure 6-b shows a plot of the predicted load-deflection (P-Δ) relationship for the control (NoFRP) and vertically stiffened (VFRP) specimens. The increase in capacity of the stiffened specimen is captured by the developed model. The model predicts gradual loss of shear capacity due to debonding followed by a sudden drop in capacity once the stiffeners are completely detached. The critical web panel buckles abruptly after the loss of the VFRP stiffeners, while maintaining a reduced resistance level almost equal to the capacity of the unstiffened specimen.





(a) Pre-debonding stress contours (b) Analytical *P*-*Δ* curves for No FRP and VFRP specimens

Figure 6. Analysis results from proposed FE model

Table 1 lists the experimental failure loads which are also compared to the analytical results obtained using the developed model. It can be seen that the failure loads are within a few percentage points, which indicates the ability of the model to capture the complex behavior of the experimentally tested specimens. As stated earlier, the DFRP specimen was not analyzed using the FE model because of the low ductility levels it exhibited, which focused the research teams' effort on the more ductile VFRP stiffener configuration.

Table 1. Types of sensors employed in this study

Specimen	Failure Load (kN [kips])		
	P_{exp}	P_{anal}	P_{exp}/P_{anal}
NoFRP (Control)	278 [62.5]	278 [62.7]	99.7%
VFRP	389 [87.5]	403 [90.8]	96.4%

4 PARAMETRIC STUDY

After validating the analysis model, a parametric study was conducted to investigate the effectiveness of SBS in strengthening over a wider range of parameters than what was experimentally tested. In this paper, the effect of initial unstiffened plate slenderness on the effectiveness of SBS using vertical stiffener configuration (VFRP) is presented. Five beam web thicknesses were chosen for the study; namely 3.2mm (1/8"), 4.0mm (5/32"), 4.8mm (3/16"), 6.4mm (1/4"), and 7.9mm (5/16"). Figure 7 shows a plot of the load-displacement relationship for the beams without SBS. It can be seen that in addition to the increase in strength, the post buckling behavior also changes due to the fact that the web starts plasticizing prior to the initiation of buckling as indicated by the wider plateaus prior to the descent of load-displacement relationship. This observation is the reason behind choosing this parameter to investigate the effect of pre-buckling plasticization on SBS.

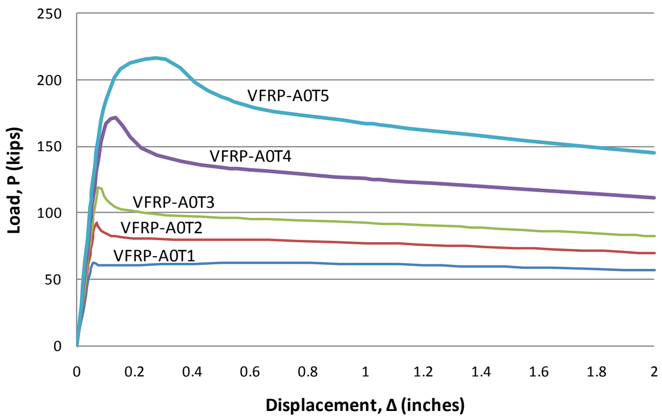


Figure 7. Load-displacement plot of unstiffened beams.

Table 2 lists the analytically obtained failure loads for all analyzed beams. It can be seen that SBS is more efficient in restraining plates that are more slender than it is with thicker plates; i.e. less slender. The beam with the thickest web plate (Case VFRP-A0T5 with 7.9mm (5/16") web) still gained about 6.7% in shear strength. The failure mode for all cases was still governed by the debonding of the FRP stiffener from the steel plate. As a result, the research team is currently expanding the parametric study to investigate the effect of the contact area on the efficiency of SBS. Other factors that may affect the performance of SBS include panel aspect ratio, fatigue, different epoxy and FRP material types. Many of these parameters are currently being investigated at Louisiana State University.

Table 2. Summary of Analysis Results

Beam Designation	Web Thickness	Ultimate Load (kN [kips])		Ultimate Load Increase Range (%)
		Unstiffened Beams	Stiffened Beams	
VFRP-A0T1	3.2mm (1/8")	278 [62.7]	403 [90.7]	44.7
VFRP-A0T2	4.0mm (5/32")	413 [93.0]	530 [119.3]	28.3
VFRP-A0T3	4.8mm (3/16")	528 [118.8]	632 [142.2]	19.7
VFRP-A0T4	6.4mm (1/4")	761 [171.2]	830 [186.6]	9.0
VFRP-A0T5	7.9mm (5/16")	961 [216.1]	1026 [230.6]	6.7

5 CONCLUSIONS

An analytical model based on the finite element method is developed. The model is designed to capture the complex behavior of beams employing the Strengthening-By-Stiffening (SBS) technique. Therefore, it simulates the instability of the slender plates under critical loads and accounts for the degeneration of the bonding material (i.e. epoxy). The model was validated using experimental results published recently by the research team. Based on the validation results, the model predicted the failure load within a few percentage points from the experimentally observed values. The effect of initial plate slenderness on the efficiency of SBS was then investigated using the validated model. The results show that the efficiency of SBS strengthening is higher for more slender plates. Other factors that may affect the efficiency of SBS have been identified including, contact area, panel aspect ratio, fatigue, different epoxy and FRP material types.

6 ACKNOWLEDGMENTS

This research is sponsored in part by the National Science Foundation (CMMI# 1030575) and the Louisiana Board of Regents (NSF2010-PFUND182). The donation of materials by Fyfe Co., LLC and support from Strongwell is greatly appreciated. Additional support from the Department if Civil and Environmental Engineering at Louisiana State University is also acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsoring agencies.

7 REFERENCES

ANSYS (2008).ANSYS,Inc., Canonsburg, PA.

Fawzia, S, Al-Mahaidi, R, Zhao, XL, and Rizkalla, S. 2007. Strengthening of Circular Hollow Steel Tubular Sections Using High Modulus CFRP Sheets. Construction and Building Materials, Elsevier Ltd, Oxford, OX5 1GB, United Kingdom, 21: 4, 839-845.

Harries, KA, Peck, AJ, and Abraham, EJ. 2009. Enhancing Stability of Structural Steel Sections Using FRP. Thin-Walled Structures, 47: 10, 1092-1101.

Okeil, AM, Bingol, Y, and Ferdous, MdR. 2009. Novel Technique for Inhibiting Buckling of Thin-Walled Steel Structures Using Pultruded Glass FRP Sections. Journal of Composites for Construction, ASCE, 13: 6, 547-557.

Okeil, A. M., Bingol, Y., and Chorkey, M. 2010. Stiffening Thin-walled Structures using Pultruded FRP Sections. 2010 FHWA Bridge Engineering Conference: Highways for Life and Accelerated Bridge Construction, April 7-9 2010, Federal Highway Administration, Washington, DC 20590, United States, Orlando, FL, United States, pp. 1039-1048.

Schnerch, D, Stanford, K, Sumner, EA, and Rizkalla, S. 2004. Strengthening Steel Structures and Bridges With High-Modulus Carbon Fiber-Reinforced Polymers - Resin Selection and Scaled Monopole Behavior. Transportation Research Record, 1892, 237-245.

Sen, R, Liby, L, and Mullins, G. 2001. Strengthening Steel Bridge Sections Using CFRP Laminates. Composites Part B-Engineering, 32: 4, 309-322.

Sen, R., Liby, L., Spillett, K., and Mullins, G. 1995. Strengthening steel composite bridge members using CFRP laminates. Non-metallic (FRP) reinforcement for concrete structures, London, England, pp. 551-558.

Shaat, A, and Fam, A. 2006. Axial Loading Tests on Short and Long Hollow Structural Steel Columns Retrofitted Using Carbon Fibre Reinforced Polymers. Canadian Journal of Civil Engineering, 33: 4, 458-470.

Tavakkolizadeh, M, and Saadatmanesh, H. 2003. Repair of Damaged Steel-Concrete Composite Girders Using Carbon Fiber-Reinforced Polymer Sheets. Journal of Composites for Construction, American Society of Civil Engineers, Reston, VA 20191-4400, United States, 7: 4, 311-322.

Zhao, XL, and Al-Mahaidi, R. 2009. Web Buckling of Lightsteel Beams Strengthened With CFRP Subjected to End-Bearing Forces. Thin-Walled Structures, 47: 10, 1029-1036.