This may be the author's version of a work that was submitted/accepted for publication in the following source:

Kamruzzaman, M, Jumaat, M.Z., Sulong, N.H.R., Qeshta, I.M.I., & Nar-mashiri, K. (2017) Effects of lateral bracing and stiffeners on the CFRP failure of strengthened steel beams. In *IOP Conference Series: Materials Science and Engineering. Vol. 210*. Institute of Physics Publishing Ltd., United Kingdom, pp. 1-16.

This file was downloaded from: https://eprints.qut.edu.au/199491/

© Consult author(s) regarding copyright matters

This work is covered by copyright. Unless the document is being made available under a Creative Commons Licence, you must assume that re-use is limited to personal use and that permission from the copyright owner must be obtained for all other uses. If the document is available under a Creative Commons License (or other specified license) then refer to the Licence for details of permitted re-use. It is a condition of access that users recognise and abide by the legal requirements associated with these rights. If you believe that this work infringes copyright please provide details by email to qut.copyright@qut.edu.au

**License:** Creative Commons: Attribution 4.0

**Notice:** Please note that this document may not be the Version of Record (i.e. published version) of the work. Author manuscript versions (as Submitted for peer review or as Accepted for publication after peer review) can be identified by an absence of publisher branding and/or typeset appearance. If there is any doubt, please refer to the published source.

https://doi.org/10.1088/1757-899X/210/1/012021
Effects of Lateral Bracing and Stiffeners on the CFRP Failure of Strengthened Steel Beams

To cite this article: M. Kamruzzaman et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 210 012021

View the article online for updates and enhancements.

Related content

- Dynamic blast response of diagonally biased stiffened steel plate under confinement
  Anju Alexander, Nikhil Mohanan and S Bincy

- Ultimate Capacity of Uniaxially Compressed Steel Plates Strengthened by CFRP
  Xin Tao and S Y Cao

- Discussion about effecting of stiffener in four bolts in a row end plate connection for long span and heavy load steel structures in Vietnam
  Khang T Huong and Cung H Nguyen
Effects of Lateral Bracing and Stiffeners on the CFRP Failure of Strengthened Steel Beams

M. Kamruzzaman¹, M.Z. Jumaat¹*, N.H.R. Sulong¹, I.M.I. Qeshta¹ and K. Narmashiri²,
¹Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
²Department of Civil Engineering, College of Engineering, Zahedan Branch, Islamic Azad University, Zahedan, Iran.

E-mail: zamin@um.edu.my

Abstract: In this paper, the effects of lateral bracing and web stiffeners on the Carbon Fibre Reinforced Polymer (CFRP) failure modes and buckling strength of the CFRP strengthened wide-flange steel I-beams are investigated experimentally. The study consisted of eight beams tested under static gradual load until failure. The main test variables were steel plate stiffeners, lateral bracings, and bonding of CFRP plates to beam soffits. The results showed that the use of steel plate stiffeners did not only prevent stress concentration below the point load, but it could also help to delay debonding of the externally bonded CFRP plate. The use of lateral bracing indicated a significant effect in preventing the CFRP splitting failure mode. In addition, the use of stiffeners with lateral bracing simultaneously, showed improvement in the in-plane flexural strength, stiffness and ductility of the CFRP strengthened I-beams.

1. Introduction
In recent decades, the strengthening and retrofitting of the structural elements of steel has become essential for enhancing their performance. Structures may need to be strengthened to avoid deterioration as a result of design or construction error; or to address any changes in function. Various methods have been used to strengthen steel structures. The most common strengthening technique of steel beams includes bolting or welding steel plates to the beam tension face. However, this approach has some drawbacks, such as corrosion in the steel plates. Another drawback is the weakness of the rehabilitated system of damaged beams to fatigue due to stress concentration in the damaged area as a result of welding or bolting joints. The use of carbon fibre reinforced polymer (CFRP) has recently gained worldwide attention in the field of strengthening and retrofitting steel structures because of its high strength-to-weight ratio, ease of placement and handling on site, and excellent resistance to corrosion [1]. Recently, CFRP strips used in the United Kingdom, United States of America, Switzerland and Japan showed that there was great potential for upgrading steel bridges and buildings with CFRP [2-6].

Steel beams strengthened with CFRP strips bonded to their tension flange have shown an increase in their in-plane bending strength [7-10]. Due to the strengthening arrangement of the steel beam, changes are usually observed in the failure mode. Failure modes observed are typical in-plane bending or sometimes buckling failure. While most studies have focused on local and global buckling [11-14], few investigations have been carried out on lateral buckling in strengthened steel beams [15-18].

In-plane bending, stress concentration below the loading point and lateral torsional buckling (LTB) are key limitations in strengthened steel beams, which are liable for premature failure of the CFRP plates. LTB occurs in laterally unrestrained strengthened steel beams that are bending about their strong axis, especially for the open sections that are under greater warping moments during torsion such as I or W sections.

The primary factors that influence the lateral torsional buckling (LTB) of steel W-beams include effective unsupported length, boundary conditions, type and position of loads, initial imperfections of...
geometry, and eccentricity of loading [19, 20]. The eccentricity of loading initiates second-order bending moment along the longitudinal axis of the steel beam, consequently promoting buckling failure [21]. The beams subjected to flexure have strength and stiffness in the plane associated with bending about their major principal axis, much greater than that associated with bending about their minor principal axis [22]. Unless these members are properly braced against lateral displacement and twisting, they would be subjected to failure by LTB before achieving full in-plane bending capacity [23].

Ghafouri and Motavalli [24] investigated the influence of LTB on pre-stress levels of CFRP strips, and on bonded and un-bonded conditions of strengthened steel beams. They observed that strengthening steel beams using CFRP strips enhanced elastic stiffness for both un-bonded and bonded techniques. In addition, pre-stressing CFRP strips did not have significant results on the elastic stiffness but substantially influenced buckling strength. The effect of LTB in the plastic region of the beams was not studied.

The capacity of steel beams could be governed by buckling failure before developing their full plastic resistance, when these elements are subjected to compressive stresses. Narmashiri, Ramli Sulong [25] conducted an experimental study on unrestrained steel I-beams reinforced with CFRP laminates to investigate CFRP failure modes. The compressive flange of the beams was adhesively bonded with CFRP composite laminates and the beams were tested under four-point bending, simply supported using hinge and roller supports. The unbraced length that had the potential to cause LTB failure in all specimens was 2,000 mm. Failure modes observed from test results were CFRP splitting and debonding below the loading point, end delamination, and end debonding. Researchers also reported that the behaviour of unrestrained retrofitted beams was affected by LTB.

Despite the number of studies on the use of stiffeners for preventing web crippling with local buckling in slender beams, less attention has been given to the effect of stiffeners on the CFRP failure mode due to stress concentration in the flange below the loading point and on LTB [26-28]. The collapse of structural elements due to stress concentration could be extremely disastrous, in terms of human life and damage to infrastructure. Stress concentration could be defined as damage at the point load section due to concentrated loads, which eventually leads to LTB. Failure of strengthening CFRP plate was found to be the most significant problem affecting the service life of existing strengthened steel structures. Therefore, the objective of this research is to investigate the influence of LTB on the flexural behaviour of strengthened wide-flange steel I-beams. The effect of stiffeners below loading points, and lateral bracing on strengthening CFRP plate and buckling failures with load carrying capacity, deformations, and strain variation of strengthened steel beams are also examined.

2. Materials and methods

2.1. Materials

2.1.1. Steel beam
The steel beams used in this research were A6-ASTM mild steel W 150×100×24 sections. Figures 1 and 2 show the dimensions of the specimens. Table 1 shows the material properties of beams. The mechanical properties of the steel beams were obtained in accordance with ASTM A370.

2.1.2. CFRP strips
In this study, Sika® CarboDur S1014 [29] pultruded carbon fibre reinforced polymer strips with cross sections of 100 × 1.4 mm were used. Table 2 shows the material properties of the CFRP strips.

2.1.3. Adhesive
Sikadur®-30 epoxy adhesive [30] was used to bond the CFRP strips onto steel beams. The properties of the adhesive are shown in table 3.
Figure 1. Elevation projection of the specimens.

Figure 2. Cross section of the specimen

Table 1. Properties of wide-flange steel I-beams

| E-Modulus (MPa) | Poison ratio | Stress (MPa) | Strain (%) |
|-----------------|--------------|--------------|------------|
| Mean value      | \( \sigma_{Steel} \) | Yielding \((F_y)\) | Ultimate \((F_u)\) | Yielding \((\epsilon_y)\) | Ultimate \((\epsilon_u)\) |
| 199,600         | 0.3          | 306          | 457        | 0.12        | 13.5          |

Table 2. Properties of CFRP plates [29]

| E-Modulus* (MPa) | Tensile Strength* (MPa) | Strain at break (%) |
|------------------|-------------------------|---------------------|
| Mean Value       | Min. 5% fracture value  | 165,000             |
| Min. Value       | 160,000                 |
| 162,000          | 180,000                 |
| 3,100            | 2,800                   |
| >2,800           | 3,000                   |
| 3,600            | 1.7                     |
| [±0.01]          |                         |
Table 3. Properties of Adhesive [30]

| E-Modulus | Strength (7 days) | E-Modulus | Strength (7 days) | Bond Strength on Steel (MPa) |
|-----------|-------------------|-----------|-------------------|-----------------------------|
| 9600      | 70-95             | 11200     | 24-31             | 14-19                       |

2.2. Experimental test

2.2.1. Preparation of the specimens

The experimental programme involved strengthening and testing a total of eight beam specimens. Four specimens were considered as reference beams (UB1, UB2, UB3 and UB4), while the other four specimens were strengthened with CFRP strips (SB1, SB2, SB3 and SB4). The strengthened specimens were bonded with 1,000 mm long CFRP strips. Table 4 presents the specifications of the beams used in this research. Figures 1 and 2 show the details of the strengthened beams. Steel plate stiffeners with a dimension of 47.7 × 10 mm were welded to the flanges and web on both sides of the beam below the loading point in specimens UB3, UB4, SB3, and SB4.

Table 4. Specifications of the specimens

| No. | Specimen ID | Specification | Method |
|-----|-------------|---------------|--------|
|     |             | Stiffeners    | Lateral bracing | CFRP |
| 1   | UB1         | N/A           | N/A     | N/A  | Exp. |
| 2   | UB2         | N/A           | √        | N/A  | Exp. |
| 3   | UB3         | √             | N/A     | N/A  | Exp. |
| 4   | UB4         | √             | √        | N/A  | Exp. |
| 5   | SB1         | N/A           | N/A     | √    | Exp. |
| 6   | SB2         | N/A           | √        | √    | Exp. |
| 7   | SB3         | √             | N/A     | √    | Exp. |
| 8   | SB4         | √             | √        | √    | Exp. |

The surface of the bottom flange of each specimen was treated by a grinding wheel to remove the rust. They were then washed with acetone to remove any material that might affect bonding. The study by Teng, Fernando [31] found that sand blasting was the most effective surface treatment for steel beams prior to bonding with external strengthening materials. Hence, the surface of all beams was sandblasted to SA 2.5. The CFRP strips were then cleaned and glued by adhesive to the tension flange of the specimens.

2.2.2. Test set-up

The beams had a total length of 2,300 mm. The specimens were tested under four-point bending until failure at a span of 2,000 mm. The distance between two point loads applied by a spreader beam was 600 mm. Figure 3 shows the test set-up and the specimen details. Mid-span vertical and horizontal deflections were measured by linear variable displacement transducers (LVDT). Strain readings were monitored by strain gauges attached to different locations of the mid-span, at the loading point and at the tip of the CFRP.
3. Results and Discussion

3.1. Load-deflection relationship and failure mode

The load-deflection relationships of specimens UB1, UB2, UB3 and UB4 are shown in figure 4. The variation of the trend of load-deflection curves provide a useful measure for the behaviour of beams. The figure shows that specimen UB1 had the lowest load carrying capacity, when compared with UB2, UB3 and UB4. The difference in load carrying capacity among the specimens was mainly related to the type of failure mode. Specimen UB1 failed as a result of stress concentration and due to the compression flange buckling below the loading plate, which in turn led to LTB. Table 5 presents a summary of test results. The load carrying capacity of specimen UB1 was mainly controlled by stress concentration and local buckling failure below the loading plate (figure 5). The presence of the stiffeners in specimen UB3 prevented stress concentration failure and hence increased the load carrying capacity up to 13.8% over specimen UB1. The increase in load carrying capacity was most apparent when the stiffener was welded such that it was touching the compression flange of the beam. LTB contributed to premature failure in specimens UB1 and UB3, which was due to the absence of lateral support for the effective length of the beam. Buckling failure involved twisting about a point below or near the tension flange [32]. In addition, the use of stiffeners and lateral bracing in specimen UB4 exhibited an increase in load carrying capacity up to 22.2% over specimen UB1.
Figure 4. Load-deflection diagram of un-strengthened specimens.

Figure 5. Stress concentration and local buckling failure mode at below the loading plate.
**Table 5. Summary of test results**

| Test unit | Yield | Peak | Failure | Ductility index | CFRP Failure mode |
|-----------|-------|------|---------|-----------------|------------------|
|           | $L_y$ (kN) | $\Delta_y$ (mm) | $E_y$ (kN/mm) | $L_p$ (kN) | $\Delta_p$ (mm) | $E_p$ (kN/mm) | $L_f$ (kN) | $\Delta_f$ (mm) | $E_f$ (kN/mm) | $\mu_{dp}$ | Ratio to UB | $\mu_{dp}$ | Ratio to UB | $\mu_{dp}$ | Ratio to UB | $\mu_{dp}$ | Ratio to UB |
| UB1       | 148.3  | 9.1  | 674.80  | 174  | 92  | 14390.0  | 167  | 105  | 16604.0  | 10.10  | 1   | 21.30  | 1   | 11.5  | 1   | 24.7  | 1   |
| SB1       | 163.0  | 9.0  | 733.50  | 198  | 32.1 | 5017.0   | 163  | 105  | 16886.0  | 3.56   | 0.35 | 6.80   | 0.32 | 11.6  | 1.01 | 22.4  | 0.94 |
| UB2       | 149    | 9.15 | 681.70  | 178  | 93  | 14730.0  | 169  | 105  | 16944.0  | 10.15  | 1   | 21.60  | 1   | 11.5  | 1   | 26.6  | 1   |
| SB2       | 165    | 8.95 | 739.00  | 202.5| 39.5 | 6624.0   | 164  | 105  | 17152.0  | 4.41   | 0.43 | 8.97   | 0.41 | 11.7  | 1.02 | 0.94  |     |
| UB3       | 160.4  | 9.2  | 736.80  | 193.5| 109 | 18923.0  | 192  | 120  | 21035.0  | 11.90  | 1   | 25.70  | 1   | 13.0  | 1   | 26.6  | 1   |
| SB3       | 168.5  | 9.08 | 765.00  | 206  | 40.5 | 6901.50  | 185  | 120  | 21371.0  | 4.46   | 0.37 | 9.02   | 0.35 | 13.2  | 1.01 | 26.5  | 0.98 |
| UB4       | 163.5  | 9.18 | 750.50  | 201.5| 115 | 2096.5   | 200  | 120  | 21705.5  | 12.60  | 1   | 27.71  | 1   | 13.1  | 1   | 30.1  | 1   |
| SB4       | 171.5  | 9.05 | 777.00  | 215  | 48.9 | 8590.8   | 196  | 120  | 22164.1  | 5.30   | 0.45 | 11.07  | 0.43 | 13.3  | 1.07 | 30.5  | 1.05 |

* $L_y$: Yield load; $\Delta_y$: Yield deflection; $L_p$: Peak load; $\Delta_p$: Peak deflection; $L_f$: Failure load; $\Delta_f$: Failure deflection; S: Splitting; ED: End debonding.
The sequence of CFRP failure modes was generally dominated by LTB and stress concentration below loading points. Figure 6 shows a comparison of load-deflection diagrams of specimens SB1, SB2, SB3 and SB4. The strength of specimen SB4 was about 9% and 7% larger than strengthened specimens SB1 and SB3 respectively, which showed that bracing and stiffeners could increase the strength but only slightly in this case due to debonding problems. The load-deflection diagram also indicated that the load dropped when the CFRP strips split and debonded from the steel beams.

![Figure 6. Load-deflection diagram of strengthened beams.](image)

![Figure 7. Variation of deflection values of beams at peak load](image)
Figure 7 shows the deflection at peak load in the strengthened beams before the failure of CFRP by debonding. Specimens SB1, SB2, SB3 and SB4 showed that the strengthened CFRP plates failed at deflection 34%, 37.5%, 37% and 43% compared to their corresponding un-strengthened beams. Specimens SB1 and SB3 failed as a result of CFRP splitting due to the influence of LTB, which led to debonding; this was in line with findings by Narmashiri, Ramli Sulong [25]. Specimen SB1 was also affected by stress concentration below the point load that caused premature failure through the earlier splitting of the CFRP plate. A long steel beam under static load, simply-supported and without bracing, can twist or buckle out-of-plane due to the lack of unbraced length [32]. The buckling strength in specimen SB2 and SB4 increased due to the use of lateral bracing, but suddenly dropped when the CFRP plate failed as a result of debonding.

![Debonded CFRP plate](image)

**Figure 8.** CFRP debonding failure in specimen SB3.

The presence of high interfacial stress near the tips of the FRP plate, which normally initiates failure in the bonding system, is considered one of the main problems in strengthened steel beams [33]. Figure 8 shows debonding of the CFRP plate in specimen SB4. Failure here was due to loss of
the bond between the adhesive and CFRP, which resulted in the separation of the CFRP plate from the bottom flange. Previous studies have explained that failure of this type occurred as a result of stress from peeling and interracial shear at the FRP tips in concrete and steel structures that have been strengthened using CFRP plates [27, 33, 34].

The failure resulting from the splitting of CFRP plate started at the loading point and spread towards the entire length of the plate. This failure mode occurred as a result of LTB failure and weakness of the plate in the transverse direction, as well as splitting caused by asymmetrical stress concentration below the loading point, as observed by Narmashiri, Ramli Sulong [25]. Researchers have reported that laterally unrestrained beams were subjected to LTB, which caused the failure of CFRP plate by splitting. Figure 9 shows the splitting of the CFRP plate in specimen SB1. The CFRP plates used in this research are unidirectional, they thus have high longitudinal (axial) strength and are weak in the transverse direction. Failure of strengthened beams usually occurred as a result of sudden lateral deformation, but it was less common in concrete beams as they have greater lateral rigidity [35, 36].

![Figure 9. CFRP splitting (specimen SB1).](image)

One of the most important parameters in strengthened/non-strengthened steel beams was boundary condition, which included support systems and types of loading. Figure 10 shows the peak load variation of the strengthened beams SB1, SB2, SB3 and SB4 and the un-strengthened beams UB1, UB2, UB3 and UB4. Specimens UB1, UB3, SB1 and SB3 were simply supported and failed by LTB, resulting in the compression flange experiencing sudden lateral deflection. The specimen experienced torsion and was twisted out of the plain of loading. As the load reached the buckling strength of the beam specimens, substantial lateral deformation was observed. Just then the external load was decreased. The lateral bracing in specimen SB4 increased the load bearing capacity to 16.42% more than UB4, at the level of 48.9 mm deflection when end-debonding (ED) initiate. It also prevents the splitting of the CFRP plate at below the point loads. A CFRP plate with ED is illustrated in figure 11. The majority of the cross-section stiffness came from the stiffener preventing stress concentration below the point load. Lateral bracing also significantly increased stiffness by increasing the buckling strength and preventing splitting of the plate at below the point load. Therefore, the use of a proper
system of stiffeners and lateral bracing could lead to remarkable enhancement in section stiffness and load bearing capacity.

![Peak loads of unstrengthened and strengthened specimens.](image)

**Figure 10.** Peak loads of unstrengthened and strengthened specimens.

![CFRP End-debonding (specimen SB3).](image)

**Figure 11.** CFRP End-debonding (specimen SB3).

3.2. *Lateral displacement*

Figure 12 shows load-lateral displacement relationships at the mid-span of strengthened beams. It illustrates that after initiation of splitting of the CFRP strip on specimen SB1, the movement changed to the opposite direction. This explains why the splitting of one CFRP strip was followed by the lateral movement returning to the original direction until failure. The horizontal movement of the specimen changed due to stress concentration below the point load and LTB. The horizontal deflection of the specimen SB3 was movement in one direction and was followed by the occurrence of LTB. Failure of the strengthened specimens SB1 and SB3 began with the splitting of the CFRP plate at a deflection of 32.3 mm and 41.1 mm, respectively (figure 7). The increase in load carrying capacity of specimens SB1 and SB3 just before failure of the CFRP plate was about 20.1% and 17.2%, compared to the un-
strengthened beams UB1 and UB3 at the same deflection values, respectively. Figure 13 shows the effect of lateral bracing on failure modes. Lateral bracing increases buckling strength by restraining the lateral displacement of the beam.

**Figure 12.** Load-lateral displacement relationships of strengthened beams.
Therefore, it can be concluded that applying lateral bracing to strengthened steel I-beams can decrease the instability of the beams as a result of LTB failure. In addition, the use of steel plate stiffeners can be effective in preventing stress concentration below the point load. Lateral bracing increases buckling strength by significantly reducing the influence of LTB.

3.3. Measured strains

The measured strain distribution of specimens SB1, SB3 and SB4 is shown in figure 14. The largest values of strain were found on the beams after yielding at loading points, which was in agreement with Al-Emrani, Linghoff [37] who found that the bonding performance of CFRP reinforced steel beams were different before and after yielding. For higher load levels, strain readings increased until maximum values were recorded at the mid-span. Strain readings then decreased gradually until the minimum values were recorded at the CFRP tip. Strain also increased abruptly due to the discontinuity of the CFRP strip. Results of this study were also similar to that by Deng, Lee [38] who showed that the large amount of strain concentration in epoxy adhesive at the tips of the strengthening strip, caused the sudden termination by debonding of the strip.

The effect of the application of stiffeners below the loading point and lateral bracing on the CFRP strip is also shown in figure 14. The strain readings show that at the load level of 150 kN and 175 kN, no significant difference was observed in strain for SB1 and SB3. At the load level of 198 kN, the strain below the loading point for specimen SB1 was higher than for specimen SB3. This showed that strain in the CFRP was significantly reduced after enhancement of the bending stiffness through the existence of stiffeners. Figure 14 also shows that the use of lateral bracing in specimen SB4 increased
the strain at the mid-span of the CFRP strip but was significantly reduced below the loading point. At 198 kN the use of stiffeners and lateral bracing in specimen SB4 caused a reduction of strain at the CFRP strip end and below the point load.

![Figure 14. The measured strain distribution along the CFRP strip for specimens SB1, SB3 and SB4 at different load levels.](image)

3.4. Ductility

The ductility of a strengthened steel beam ensures the capability of a structure to endure considerable plastic deformation without substantial loss of strength. In this research, the ductility indices of strengthened beams were obtained based on displacement ($\mu_d$) and energy ($\mu_E$) ratios [39]. The displacement ductility index at peak load ($\mu_{dp}$) and at failure load ($\mu_{df}$) are expressed as follows:

$$\mu_{dp} = \frac{\Delta_y}{\Delta_p}$$  \hspace{1cm} (1)  
$$\mu_{df} = \frac{\Delta_f}{\Delta_y}$$  \hspace{1cm} (2)

Where, $\Delta_y$, $\Delta_p$ and $\Delta_f$ are displacements at yield, peak and failure loads, respectively.

The energy ductility index ($\mu_E$) at peak load ($\mu_{Ep}$) and at failure load ($\mu_{Ef}$) are expressed as follows:

$$\mu_{Ep} = \frac{E_p}{E_y}$$  \hspace{1cm} (3)  
$$\mu_{Ef} = \frac{E_f}{E_y}$$  \hspace{1cm} (4)

Where, $E_y$, $E_p$ and $E_f$ are energy at yield, peak and failure loads, respectively.

The calculated ductility indices of all beams are presented in table 5. The ratio of the ductility indices for displacement of specimens SB1, SB2, SB3 and SB4 were 0.35, 0.43, 0.37 and 0.45; while that for energy were 0.32, 0.41, 0.35 and 0.43, respectively, which corresponded to control specimens at peak loads. This indicated that strengthened beams with the CFRP plate suffered from the loss in ductility.
Several researchers have reported that the ductility of strengthened beams could be reduced as a result of reinforcements by externally bonded FRP plates [40, 41], which could be attributed to the brittle behaviour of the CFRP plate. FRP materials also have a linear stress–strain relationship up to the point of failure. It was observed that the ductility ratio for strengthened specimens SB1, SB2, SB3 and SB4 at failure load increased for the displacement ductility by 1.01, 1.02, 1.01 and 1.07; while that for energy ductility increased by 0.94, 0.94, 0.98 and 1.05, mainly as a result of the ductile properties of steel beams. The ductility of specimen SB1 was less than specimens SB3 and SB4 due to stress concentration and LTB failure. The effect of stiffeners and lateral bracing on beam behaviour indicated an increase in ductility, caused by a delay in the debonding of the reinforcing plate from the surface of steel beams. Therefore, stiffeners prevented stress concentration below the loading points. Lateral bracing delayed the failure of the CFRP plate by preventing below load-splitting (BS) CFRP failure, consequently increasing displacement and energy ductility of the strengthened beams.

4. Conclusions
The buckling strength of CFRP strengthened wide-flange steel I-beams was experimentally examined. The effect of different parameters, such as stiffeners and lateral bracing, on the CFRP failure mode and ultimate load bearing strength of steel beams was also studied. Results indicate that the stress concentration of the compression flange in beams without steel plate stiffeners increased greatly during loading and caused local buckling failure below the loading points and initiates early end-debonding. This failure was also affected by the lateral torsional buckling (LTB) of strengthened and non-strengthened beams. The use of steel plate stiffeners prevented stress concentration below the point load and improved delay in the debonding of the externally bonded CFRP plate. The use of lateral bracing showed a significant effect in avoiding the initiation of the below load-splitting CFRP failure and increased the ductility of the strengthened beams. Additionally, the prevention of LTB failure was found to delay the end debonding of CFRP strips. The stiffeners with lateral bracing increased in-plane flexural strength and stiffness. In addition, the stiffeners and lateral bracing also contributed to retard the failure of the CFRP plate. Beams that were externally bonded with CFRP plates showed a reduction in ductility compared to their corresponding non-strengthened beams. This caused the brittle properties and premature debonding failure of the FRP strips. The flexural strength and ductility of beams were found to be generally limited by end-debonding failure.

Acknowledgements
The authors gratefully acknowledge the financial support by the University of Malaya High Impact Research Grant (HIRG) No. UM.C/625/1/HIR/MOHE/ENG/36 (16001-00-D000036) – “Strengthening Structural Elements for Load and Fatigue”.

References

[1] CNR D 2007 Guidelines for the design and construction of externally bonded FRP systems for strengthening existing structures – Metallic structures – Preliminary study. National Research Council, Rome.

[2] Zhao X-L and L Zhang 2007 Eng. Struct. 29 1808-1823

[3] Suzuki H 2005 Advanced materials for construction of bridges, buildings and other structures.

[4] Kamruzzaman M, M Z Jumaat, N Ramli Sulong and A Islam 2014 Sci. World J. 2014.

[5] Ghafoori E, M Motavalli, A Nussbaumer, A Herwig, G Prinz and M Fontana 2015 Compos. Pt. B-Eng. 68 1-13

[6] Ghafoori E, G S Prinz, E Mayor, A Nussbaumer, M Motavalli, A Herwig and M Fontana 2014. Polymers. 6 1096-1118

[7] Zhao X-L 2013 FRP-strengthened metallic structures. CRC Press.

[8] Bennati S, D Colonna and P S Valvo 2016 P. Struct. Int. 2 2682-2689
[9] Deng J, Y Jia and H Zheng 2016 Compos. Struct. 136 450-459
[10] Lin W, T Yoda, N Taniguchi and M Hansaka 2013 J. Constr. Steel. Res. 85 130-139
[11] Naderian H, H Ronagh and M Azhari 2014 Thin-Walled Struct. 84 289-301
[12] Dahmani L and A Boudjemia 2014 Strength Mater-Engl. Tr. 46 429-432
[13] Wang Y, L Yang, B Gao, Y Shi and H Yuan 2014. Int. J. Steel Struct. 14 411-420
[14] Ragheb W F 2015 J. Constr. Steel. Res. 107 81-93
[15] Kala Z 2013 P. Eng. 57 504-514
[16] Kabir M and A Seif 2010 J. Scientia Iranica Trans. A-Civil Eng. 17 262-272
[17] Nguyen T, T Chan and J T Mottram 2013 Compos. Struct. 100 233-242
[18] Shaat A and A Z Fam 2009 J. Compos. Constr. 13 2-12
[19] Benyamina A B, S A Meftah, F Mohri and E M Daya 2013 Eng. Struct. 56 1207-1219
[20] Ozbasaran H 2014 A Parametric Study on Lateral Torsional Buckling of European IPN and IPE Cantilevers.
[21] Humbel. T 2014 Ultra-high modulus CFRP for fatigue strengthening of steel beams - experimental and theoretical investigation : Empa/ETHZ, Dübendorf, Switzerland.
[22] Galambos T V 1998 Guide to stability design criteria for metal structures. John Wiley & Sons.
[23] Ziemen R D 2010 Guide to stability design criteria for metal structures. John Wiley & Sons.
[24] Ghafoori E and M Motavalli 2015 Constr. Build. Mater. 76 194-206
[25] Narmashiri K, N Ramli Sulong and M Z Jumaat 2012 Constr. Build. Mater. 30 1-9
[26] Moy S and F Nikoukar 2002 Advanced Polymer Composites for Structural Applications in Construction: Proceedings of the First International Conference, Held at Southampton University, Uk, on 15-17 April 2002. Thomas Telford.
[27] Deng J and M M Lee 2007 Compos. Struct. 78 232-242
[28] Teng J, T Yu and D Fernando 2012 J. Constr. Steel. Res. 78 131-143
[29] Sika®CarboDurPlates 2013 Product Data Sheet- Pultruded carbon fiber plates for structural strengthening. [Edition 2013-03_1].
[30] Sikadur®-30 2014 Product data sheet, 2- part epoxy impregnation resign for bonding reinforcement [Edition 2014-01_1].
[31] Teng J, D Fernando, T Yu and X Zhao 2011 Advances in FRP Composites in Civil Engineering. 2011, Springer. p. 865-868.
[32] Yura J and B A Phillips 1992 Bracing requirements for elastic steel beams. Center for Transportation Research, University of Texas.
[33] Haghani R, M Al-Emrani and R Kliger 2009 Constr. Build. Mater. 23 1413-1422
[34] Narmashiri K and M Z Jumaat 2011 Simul. Model. Pract. Theory. 19 564-585
[35] Buyukozturk O, O Gunes and E Karaca 2004 Constr. Build. Mater. 18 9-19
[36] Narmashiri K 2011 Carbon Fibre Reinforced Polymer Strips for Flaxural and Shear Strengthening of Steel I-beams, University of Malaya.
[37] Al-Emrani M, D Linghoff and R Kliger 2005 Bonding strength and fracture mechanisms in composite steel-CFRP elements. International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005). International Institute for FRP in Construction.
[38] Deng J, M M Lee and S S Moy 2004 Compos. Struct. 65 205-215
[39] Hawileh R A, H A Rasheed, J A Abdalla and A K Al-Tamimi 2014 Mater. Des. 53 972-982
[40] Rasheed H A, R R Harrison, R J Peterman and T Alkhrdaji 2010 Compos. Struct. 92 2379-2390
[41] Morsy A M, K M Helmy, N H El-Ashkar and M Nada 2014 Conc. Sol. 313