

Article

Impact of Unbonded CFRP Strengthening on the Bending Performance of Steel I-Beams: A Numerical Study

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Abstract

The performance of steel structures can decrease over time due to several factors and therefore requires serious consideration to avoid any risks to users. Currently, strengthening of structures using fiber-reinforced polymer (FRP) materials is gaining in popularity. This paper presents a finite element (FE) analysis to investigate the flexural performance of steel I-beams strengthened with unbonded carbon FRP (CFRP). A total of 38 beam models is developed with four influential parameters considered, namely CFRP thickness, CFRP elastic modulus, type of steel beam cross-section, and strengthening length. The results of the investigation confirm that unbonded CFRP strengthening improves the performance of steel I-beams. Initial stiffness and moment capacity of the beams increase as the thickness of CFRP, CFRP elastic modulus, and strengthening length increase. The increase in the initial stiffness of beams tends to be linear as the length of strengthening increases. Meanwhile, the linear trend occurs only up to CFRP lengths of 700 mm or 800 mm for the increase in beam moment capacity. Unbonded CFRP strengthening contributes higher to steel beams with a lower moment of inertia.

Keywords: strengthening; performance; unbonded CFRP; finite element; steel I-beams

1. Introduction

1.1. Research Background

The performance of steel structure elements, such as beams or columns, can decrease over time due to various factors, including their environment. In order to prevent danger to users, the appropriate repairs or strengthening must be carried out. Strengthening using traditional techniques, such as bolting and welding additional steel plates to existing structures, is no longer considered relevant in the present age. Bolting and welding can be very complicated and expensive, particularly when strengthening of structural elements is undertaken on a large scale, which can render the process ineffective. Using additional steel plates will create new problems, such as corrosion and increased structural loads.

In recent decades, the use of fiber-reinforced polymer (FRP) in construction as a strengthening material has grown rapidly. It has gained popularity in structural applications because of its many advantages [1–5]. This material is lightweight [6–8] compared to other strengthening materials. This makes FRP easier for application [9,10]. Although lightweight, FRP is a high-strength material [11–13]. It also exhibits exceptional performance in terms of fatigue [14–16] and corrosion resistance [17–19].

The effectiveness of FRP in repairing and enhancing the performance of steel structures has been demonstrated by researchers in many investigation programs, as conducted by



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Deng and Lee [20], who studied the behavior of steel beams strengthened with CFRP plates. The CFRP plate is bonded to the underside of the beam. The presence of CFRP is proven to increase the load-carrying capacity of the beam. The strength of the beam increases as the length of the CFRP plate used increases. Colombi and Poggi [21] also studied the flexural behavior of CFRP-strengthened steel beams. Before the CFRP plates are bonded to the bottom side of the beams, the steel surface is first treated with an abrasive disk, and any dust is removed using a special liquid. They found that, with CFRP strengthening, the yield load of the beam can increase by up to 65%. Haedir et al. [22] evaluated changes in the performance of circular hollow section (CHS) steel beams strengthened with CFRP sheets bonded to its surfaces. Similar to what Colombi and Poggi [21] did, they also used an abrasive disk for steel surface preparation. Their research findings revealed that the increase in beam strength is significantly influenced by the number and orientation of CFRP fibers.

Hmidan et al. [23] studied the effect of CFRP in improving the performance of steel beams with initial cracks. A number of steel beam specimens are prepared, and their surfaces are grit-blasted before CFRP sheets are applied. It is confirmed by the test results that the load-bearing capacity of the beams increases after strengthening with CFRP. The effectiveness of CFRP is particularly evident in beams with a higher level of initial cracking. Kabir et al. [24] tested CHS steel beams strengthened using CFRP sheets. The CFRP sheets are bonded to beam surfaces with different layer orientations. The presence of CFRP can increase the beam's maximum load-bearing capacity by up to 53%. Significant increases are also observed in the elastic and plastic stiffness of beams, yet at higher loads. Altaee et al. [25] strengthened steel beams with openings using 3 mm thick unidirectional CFRP plates. The CFRP plates are bonded after steel surfaces are treated with mechanical grinding and any remaining dust is cleaned with acetone. They found that strengthening can both recover and increase the beam's strength by up to 20%. Additionally, the beams also experienced an increase in stiffness compared to beams without openings.

Siwowski and Siwowska [26] compared the flexural behavior of steel beams strengthened with CFRP plates for two strengthening schemes: adhesive-bonded passive plates and adhesive-bonded prestressed plates. The strengthening can lead to a 10% increase in ultimate flexural capacity. The yield flexural capacity of the beams is significantly influenced by the CFRP elastic modulus. Kadhim et al. [27] investigated performance of CFRP-strengthened steel beams under impact loads. The CFRP is bonded to the steel surface after mechanical abrasion is imposed on it. The research parameters examined are CFRP thickness and length. The CFRP thicknesses of 1.2 mm and 2.4 mm can reduce maximum transverse displacement by approximately 10% and 14%, respectively. A shorter CFRP results in a decrease in the impact force plateau value.

Peiris and Harik [28] used an ultra-high modulus (UHM) CFRP strip to strengthen wide-flange steel beams. The steel surface is grit-blasted before applying CFRP to obtain a strong bond. Their findings reveal that beams strengthened with 10 mm and 5 mm strip panels have failure loads 27% and 26% higher, respectively, than the yield load of the unstrengthened control beams. This percentage increases to 39% when using 50 mm wide strip panels. Tafsirojjaman et al. [29] performed an experimental investigation on the response of full-scale simply supported circular hollow steel members subjected to monotonic and large-displacement cyclic loading. A sandblasting treatment is applied to the entire outer surface of the CHS steel before it is wrapped with CFRP laminates. It is confirmed from this investigation that the ultimate moment capacity of the beam increases by 51% in the monotonic test and 35.4% in the cyclic loading test.

Based on previous studies, it can be concluded that strengthening of steel structures using FRP materials is generally performed by the adhesive-bonding method, in which

FRP is adhered directly to steel surface. This method has drawbacks as it requires special treatments on steel surface prior to FRP installation for acceptable bonding between CFRP and steel. This activity is complicated because it cannot be done carelessly and must involve skilled and experienced workers. Different types of steel surface treatment may result in varying bond strength [30]. To date, there are no established standards regarding the optimal surface condition of treated steel for the application of FRP as a reinforcement. Consequently, large variations in bond strength between CFRP and steel are inevitable across the strengthened area due to non-uniformity of steel surface conditions following treatments. In addition, variation in bond strength between CFRP and steel is also caused by inconsistencies in the thickness and distribution of adhesive across the bonding area. It is impossible to achieve 100% uniform adhesive thickness, especially when CFRP is bonded by the hand layup technique.

In this paper, the authors investigate the structural behavior of steel beams strengthened with the unbonded CFRP method. In this method, the CFRP is attached to steel without being bonded to its surface, so no steel surface treatments are required. The contribution of CFRP is derived solely from its flexural rigidity. This investigation is performed through finite element (FE) analysis. A total of 38 finite element models are developed to explore the effect of several influential parameters, namely: CFRP thickness, CFRP elastic modulus, type of steel beam cross-section, and strengthening length.

1.2. Method of Strengthening Using Unbonded CFRP

The method of strengthening steel using unbonded CFRP has been proposed by the first author in previous studies [5,7,12]. In this method, CFRP is not bonded by adhesive to the steel surface, so that complicated steel surface treatments such as sandblasting, grit blasting, hand grinding, etc., are no longer required at all. This offers advantages for on-site applications as the duration of the work can be potentially reduced significantly, thereby lowering construction costs. The CFRP is molded directly onto the steel parts where the strengthening will be implemented, using a vacuum-assisted resin transfer molding (VaRTM) process. Figure 1 shows a VaRTM process for unbonded CFRP in angle steel. Generally, the process begins by cleaning steel surfaces from dust and other contaminants. Then, the steel is immediately wrapped with a peel ply that serves as a separator between the steel and CFRP and is also intended as an effort to eliminate (or minimize) bonds between CFRP and steel. Carbon fibers with predetermined quantities and sizes are applied one by one over the peel ply. The orientation of carbon fibers is adjusted as needed. Afterwards, another layer of peel ply is added to cover the carbon fibers, followed by the installation of VaRTM utilities such as resin media, infusion spiral tube, film bag, and resin feed line (hose). To ensure no external air enters during the vacuum process, a firm gum tape connection is carefully implemented. The next step is the resin impregnation process, which is conducted by suction using a vacuum pump at an adjusted pressure. After the vacuum process is complete, the VaRTM utilities are kept unchanged for at least 24 h to ensure the initial CFRP formation process proceeds properly and subsequent demolding activity can be performed easily. The CFRP is then cured for at least one week to ensure better laminate quality is obtained. Mechanical characteristics of CFRP laminates formed by VaRTM technique are more stable compared to those produced by hand layup.

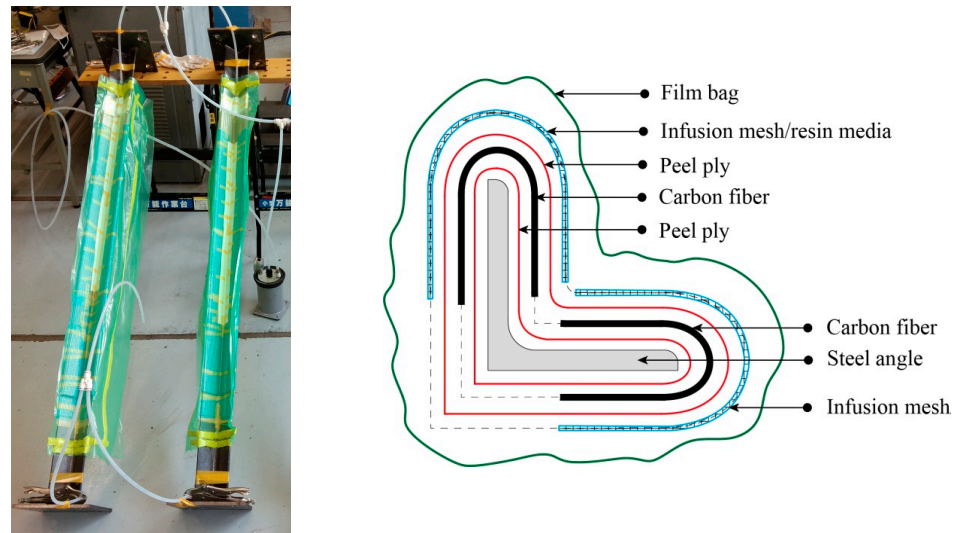


Figure 1. The VaRTM process for unbonded CFRP on angle steel [7].

2. Materials and Methods

The structural behavior of steel I-beams strengthened with unbonded CFRP under bending loads has never been studied experimentally by anyone; consequently, experimental data on the structural behavior of steel I-beams strengthened with unbonded CFRP under bending loads are also unavailable. Therefore, in this paper, the authors investigate the bending behavior of steel I-beams that are strengthened with unbonded CFRP through the simulation of a finite element model developed based on a validated FE model of bare steel I-beams and unbonded CFRP strengthening.

2.1. Modeling and Validation of Bare Steel Beam

A numerical model of bare steel I-beam is developed and validated against the results of an experimental test conducted by Kamruzzaman et al. [31]. In their experiment, a total of four bare steel I-beams is tested. The beams are distinguished based on whether stiffeners and lateral bracing are involved. In the present study, only one beam is selected for modeling and validation, namely steel I-beam without stiffeners but with lateral bracing. This type of beam is then adopted for the bending simulation of steel I-beams strengthened with unbonded CFRP in Section 2.3.

The beam is developed in a full-scale three-dimensional (3D) model. The material properties of steel are the same as those used in experiments and there is no difference between flange and web parts. The elastic modulus, yield stress, and ultimate strength are 199.6 GPa, 306 MPa, and 457 MPa, respectively, with a Poisson's ratio of 0.3. To consider the non-linearity (plasticity) of steel, the stress–strain relationship is assumed to follow a bilinear curve with a tangent modulus equal to 0.01 of the elastic modulus. The steel beam is represented by solid tetrahedron elements with a relatively fine mesh (14 mm).

The beam model is simply supported with two concentrated loads. The left support is restrained in both vertical and longitudinal directions, while the right support is restrained only in the vertical direction. Lateral bracing is installed on the beam to prevent lateral-torsional buckling.

The results of finite element simulation—load versus mid-span deflection of the beam—are compared with experimental results to confirm the validity of the finite element model developed. It can be seen from Figure 2 that excellent agreement has been achieved between the experimental result and the finite element simulation for the load–deflection curve at the mid-span of the beam. The yield and peak loads obtained from the simulation are 150 kN and 180 kN, respectively. These values are 0.6% and 1.1% higher than the

experimental results, respectively. Moreover, the deflection at yield and peak loads are 9 mm and 98 mm, respectively. The difference between the experimental and simulation results is only 1.6% and 5.4%, respectively. All these well-matched conditions confirm the accuracy of the finite element model developed.

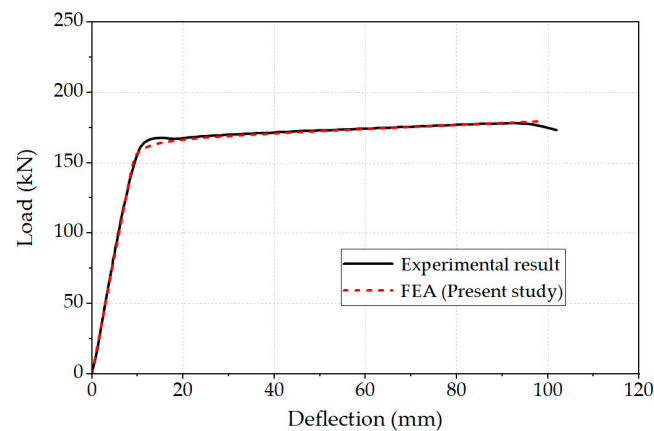


Figure 2. Comparison between experimental result [31] and simulation result.

2.2. Modeling and Validation of Unbonded CFRP Strengthening

To validate the finite element model of unbonded CFRP strengthening, the study conducted by the first author [3] can serve as a reference. In that work, the author examined validation of a finite element model of unbonded CFRP strengthening through an experimental buckling test of steel elements. All modeling criteria and procedures are described. The results reveal that comparison of load versus lateral deflection at mid-height curves and comparison of the steel load-carrying capacity are highly satisfied. Figure 3 shows the load–displacement curves for two selected specimens, namely those with unbonded CFRP lengths of 260 mm and 340 mm. The peak load obtained from the simulation for the first specimen (Figure 3a) is 230.6 kN. This value is only 0.9% higher than the experimental result. Moreover, the peak load obtained from the simulation for the second specimen (Figure 3b) is 235.7 kN, which is only 0.4% higher than the experimental result. It is confirmed from these results that unbonded CFRP strengthening can be well modeled numerically and further used for strengthening steel I-beams.

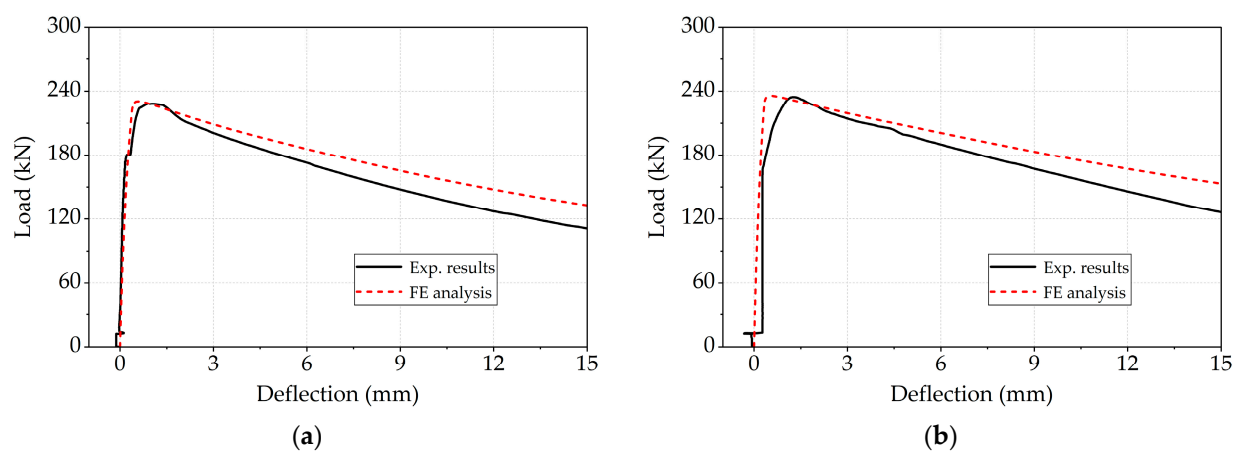


Figure 3. Comparison of load-lateral deflection curves obtained from simulation and experiment [3]: (a) specimen with unbonded CFRP length of 260 mm (BL56F26-2); (b) specimen with unbonded CFRP length of 340 mm (BL56F34-2).

2.3. Bending Simulation of Unbonded CFRP Strengthened Steel I-Beams

The aim of this section is to explore the application of the unbonded CFRP strengthening method on steel I-beams. A 2300 mm long steel I-beam is simply supported with a span length of 2000 mm. A four-point bending scheme is applied to the beam, with a distance between two loads of 600 mm and a distance from one load point to the nearest support of 700 mm. There are two types of beam cross-section (A and B) included in this simulation, which also constitute one of the four study parameters. Type A has the following dimensional sizes: thickness of flange (t_f) = 10.2 mm, width of flange (b_f) = 102 mm, thickness of web (t_w) = 6.6 mm, and total height of section (H) = 160 mm. Type B has the following dimensional sizes: thickness of flange (t_f) = 11 mm, width of flange (b_f) = 203 mm, thickness of web (t_w) = 7.2 mm, and total height of section (H) = 203 mm. The beam does not have steel plate stiffeners on either side. Lateral supports of the beam are located at 500 mm from each support. Unbonded CFRP strengthening is positioned at the mid-span and only on the bottom flange. A schematic view of the beam is shown in Figures 4 and 5.

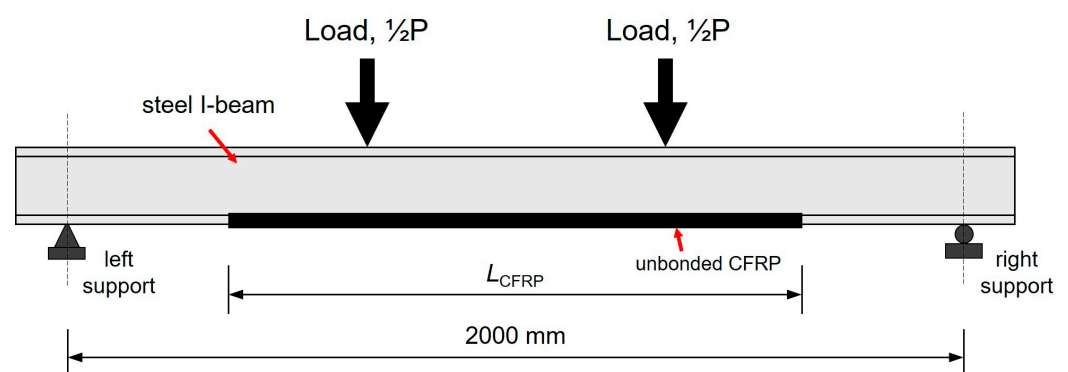


Figure 4. Schematic strengthening layout of steel I-beams.

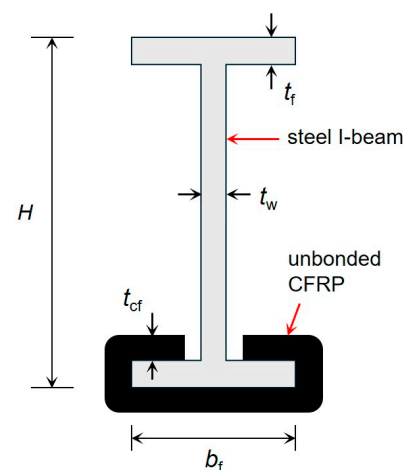


Figure 5. Beam cross-sections along the strengthening length (L_{CFRP}).

The unbonded CFRP strengthened steel I-beams are simulated using commercially available finite element software, Autodesk Inventor Nastran. Detail of the finite element model is shown in Figure 6. The beam is fully developed in three-dimensional (3D) form. Both steel and CFRP are modeled using solid tetrahedron elements. In order to obtain favorable results without spending excessive time on analysis, preliminary numerical simulations are conducted on the beam using three different mesh sizes (8 mm, 10 mm, and 14 mm). It is confirmed that identical load–deflection relationships of the beam are obtained, as illustrated in Figure 7. Therefore, the mesh size of 14 mm is adopted for all

beam models in this study, as it required a shorter computation time compared to the other mesh sizes. A bilinear stress–strain behavior is adopted for steel, with the tangent modulus assumed to be 1% of the elastic modulus. Although CFRP is an orthotropic material, it is assumed to be an elastic isotropic material in this study for the sake of simplification. This is not a problem as long as the adopted modulus of elasticity is the longitudinal modulus of elasticity and the CFRP’s longitudinal axis is coincided with the beam’s longitudinal axis, given that the dominant behavior of the beam under bending is governed by its longitudinal direction. Both CFRP and steel have a Poisson’s ratio of 0.3. To simulate unbonded behavior, a “separation” surface-to-surface contact type with a friction coefficient of 0.1 is applied between the steel and CFRP surfaces. Steel surface is the primary entity, while CFRP is the secondary entity. A friction coefficient of 0.1 is employed to rationally simulate the unbonded condition of CFRP. Based on a brief numerical comparison, this friction coefficient is revealed to have very low sensitivity (<1%). The beam is restrained in longitudinal and vertical directions at the left support, while it is only restrained in the vertical direction at the right support. The beam is also restrained laterally at a distance of 500 mm from each support.

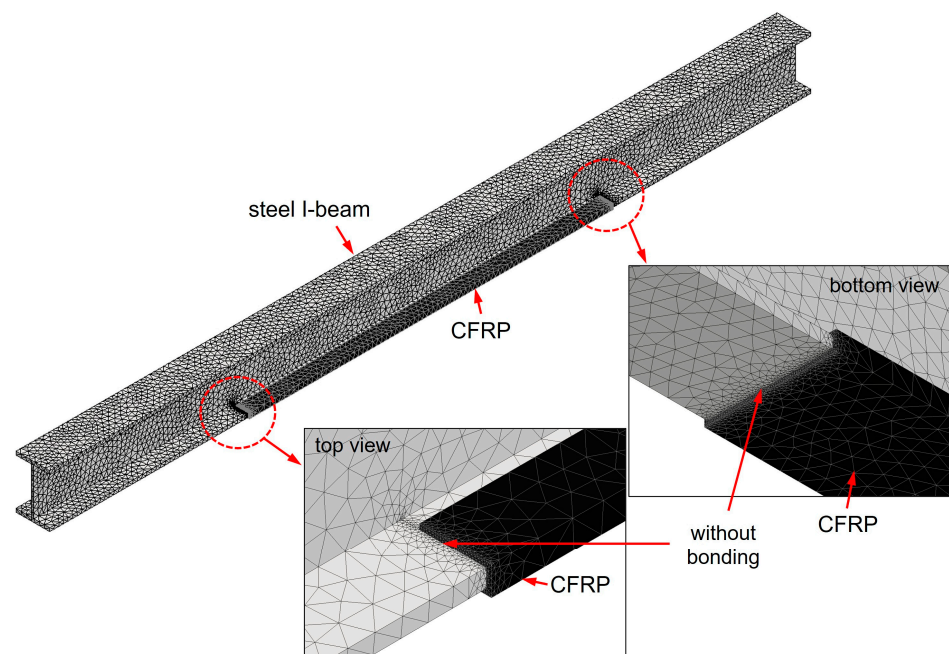


Figure 6. Detail of finite element (FE) modeling.

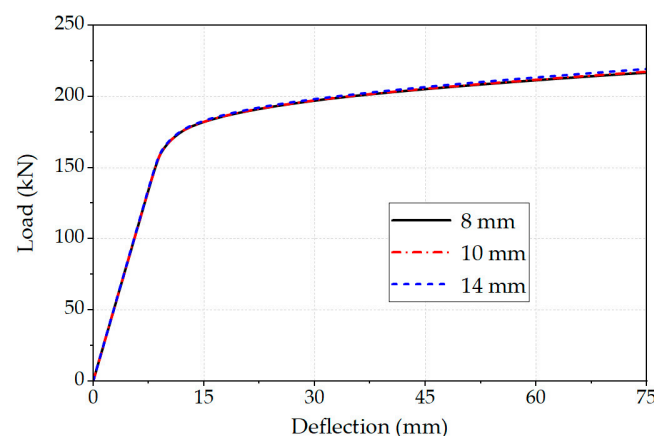


Figure 7. Comparison of load–deflection curve of beam using different mesh sizes (8 mm, 10 mm, dan 14 mm).

A total of 38 models are developed to investigate the effects of several parameters on the flexural behavior of beams. The influential parameters include: (i) CFRP thickness (t_{cf}), (ii) CFRP elastic modulus (E_{cf}), (iii) type of beam cross-section, and (iv) strengthening length. For easier identification, each beam is labeled as shown in Table 1. The combination of letter and number at the beginning indicates the type of steel beam cross-section (A or B) and CFRP thickness (5 mm, 7 mm, and 9 mm). The middle number represents the CFRP elastic modulus (50 GPa, 100 GPa, and 200 GPa). The last number is the length of the CFRP (450 mm, 600 mm, 750 mm, 800 mm, 900 mm, and 1100 mm). For example, A7-50-900 identifies a beam model with an A-type cross-section, with a CFRP thickness and length of 7 mm and 900 mm, respectively, and a CFRP elastic modulus of 50 GPa. For control beams without strengthening, labeling is performed by simply mentioning the steel beam cross-section type preceded by the term “CBeam” (CBeam-A and CBeam-B).

Table 1. Summary of investigation results.

Beam ID	Moment Capacity (kN·mm)	Increase over Unstrengthened Model (%)	Stiffness (kN/mm)	Increase over Unstrengthened Model (%)
CBeam-A	58,156.0	-	16.9	-
A7-50-450	60,529.0	4.1	17.7	5.1
A7-50-600	63,584.5	9.3	18.0	7.0
A7-50-750	66,836.0	14.9	18.3	8.7
A7-50-800	67,452.0	16.0	18.4	9.3
A7-50-900	67,781.0	16.6	18.6	10.2
A7-50-1100	67,935.0	16.8	18.8	11.6
A5-50-450	60,382.0	3.8	17.5	3.7
A5-50-600	63,196.0	8.7	17.7	5.0
A5-50-750	65,747.5	13.1	17.9	6.2
A5-50-800	66,160.5	13.8	18.0	6.6
A5-50-900	66,370.5	14.1	18.1	7.2
A5-50-1100	66,528.0	14.4	18.2	8.2
A3-50-450	60,217.5	3.5	17.2	2.1
A3-50-600	62,317.5	7.2	17.3	2.9
A3-50-750	63,997.5	10.0	17.5	3.6
A3-50-800	64,263.5	10.5	17.5	3.9
A3-50-900	64,274.0	10.5	17.6	4.2
A3-50-1100	64,211.0	10.4	17.6	4.5
A7-100-450	60,711.0	4.4	18.3	8.8
A7-100-600	64,064.0	10.2	18.9	12.2
A7-100-750	68,274.5	17.4	19.4	15.4
A7-100-800	69,230.0	19.0	19.6	16.3
A7-100-900	69,944.0	20.3	19.9	18.0
A7-100-1100	70,164.5	20.6	20.3	20.7
A7-200-450	60,949.0	4.8	19.1	13.6
A7-200-600	64,442.0	10.8	20.1	19.0
A7-200-750	69,307.0	19.2	20.9	24.3
A7-200-800	70,598.5	21.4	21.2	25.9
A7-200-900	71,806.0	23.5	21.7	28.8
A7-200-1100	72,208.5	24.2	22.5	33.5
Cbeam-B	149,026.5	-	50.4	-
B7-200-450	153,251.0	2.8	52.6	4.2
B7-200-600	158,193.0	6.2	53.3	5.7
B7-200-750	163,187.5	9.5	54.0	7.0
B7-200-800	164,591.0	10.4	54.2	7.4
B7-200-900	165,641.0	11.1	54.6	8.2
B7-200-1100	165,172.0	10.8	55.1	9.1

3. Results and Discussion

Table 1 presents a summary of investigation results obtained based on finite element simulations, which includes the initial stiffness and moment capacity of the beams. The table also shows the percentage increase in the initial stiffness and moment capacity over the unstrengthened control beam model. The initial stiffness is a slope in the load–deflection curve during the initial phase of loading, while the moment capacity of beams considered in this study is the moment capacity at which beam deflection reaches 20 mm. This restriction is adopted for the sake of uniformity and easier comparison, given that the deflection at failure of each beam is confirmed to be different due to the presence of unbonded CFRP. The load–deflection response of all beams can be seen in Figure 8.

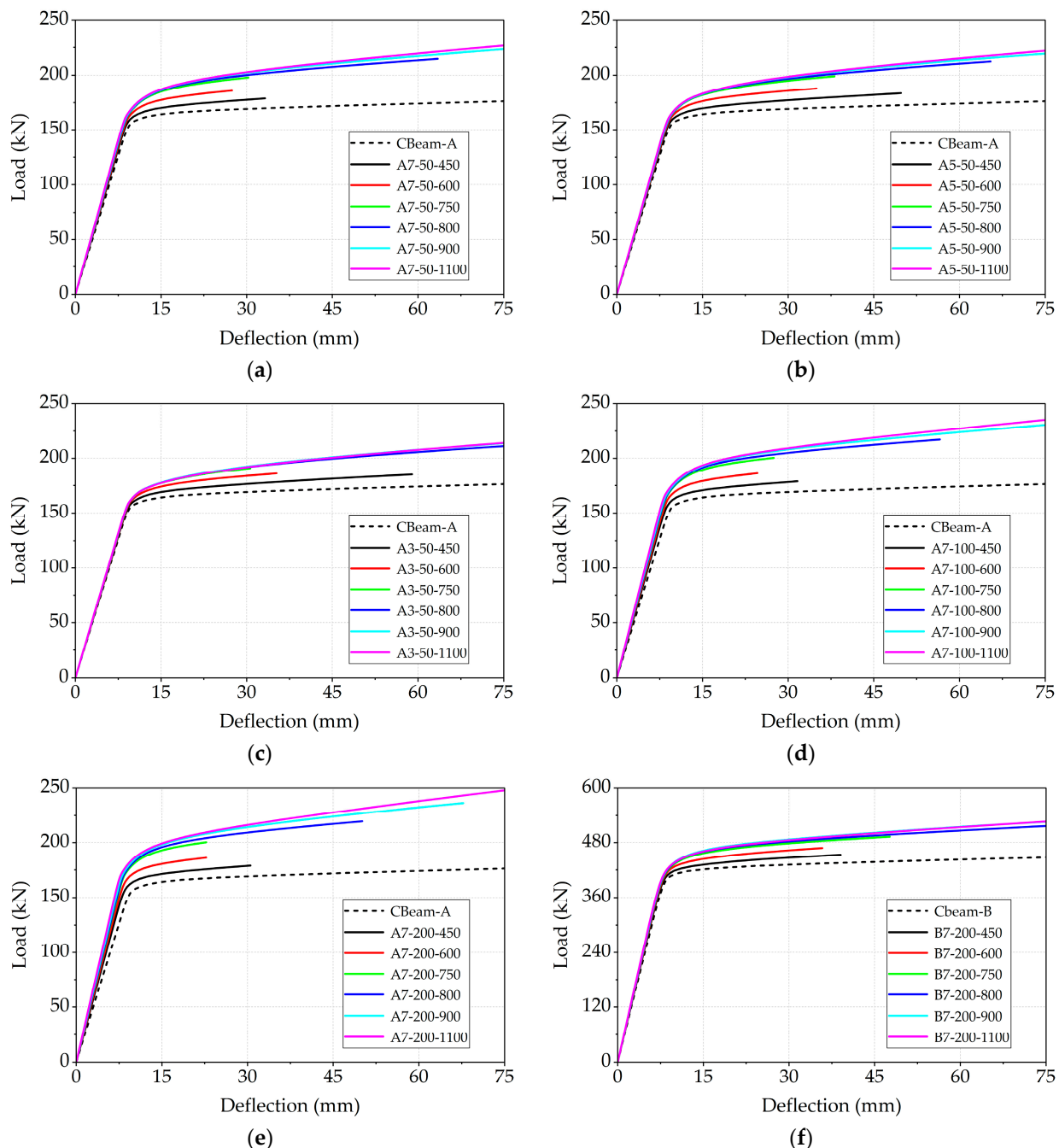


Figure 8. Load–deflection response of all beam models: (a–c) beam type A with CFRP thickness of 7 mm, 5 mm and 3 mm, respectively; (d,e) beam type A with CFRP elastic modulus of 100 GPa and 200 GPa, respectively; (f) beam type B.

3.1. Thickness of CFRP

The effect of CFRP thickness on the initial stiffness of the beams is illustrated in Figure 9a. Moreover, it can also be viewed in Figure 8 and Table 1. As shown in Figure 9a, the presence of unbonded CFRP increases initial stiffness of the steel beams. The most significant increase is observed in the application of CFRP with a thickness of 7 mm, followed by CFRP with a thickness of 5 mm. The use of 3 mm thickness CFRP results in an increase in initial stiffness of the steel beam with the lowest percentage. There is a decrease in the percentage gain of initial stiffness of the steel beam as the CFRP thickness decreases, and inversely, it is directly related to moment of inertia of the CFRP cross-section itself. It is evident that CFRP with greater thickness will possess a higher moment of inertia, thereby contributing more to the initial stiffness of steel beams. Conversely, CFRP with a lower thickness has a lower moment of inertia and thus contributes less to the initial stiffness of steel beams. The highest increase in the initial stiffness of steel beams is observed in beam model A7-50-1100 (i.e., 11.6%), whilst the smallest increase is found in beam model A3-50-450 (i.e., 2.1%). For each CFRP length employed, the difference in percentage increase in the initial stiffness of the steel beams remained consistent when CFRP thickness changed from 3 mm to 5 mm and from 5 mm to 7 mm. However, the largest difference occurs when the CFRP length is 1100 mm (3.7% and 3.4%), and the smallest difference occurs when the CFRP length is 450 mm (1.6% and 1.4%).

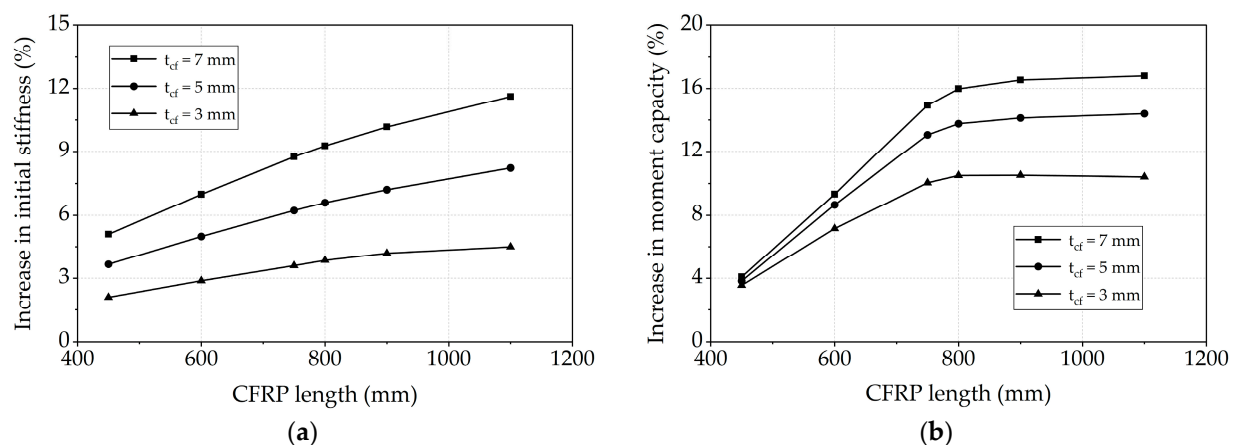


Figure 9. The effect of different CFRP thickness on performance of steel I-beam: (a) initial stiffness; (b) bending moment capacity.

Figure 9b shows the effect of CFRP thickness on the moment capacity of steel beams. The moment capacity, in this instance, is defined as the point at which the beam deflection reaches 20 mm, as previously outlined. As with the initial stiffness, the moment capacity of the beams is also confirmed to increase due to the presence of unbonded CFRP. An increase of 16.8% became the highest value, which is found in the beam model A7-50-1100. Meanwhile, the lowest increase, which is only 3.5%, is found in the beam model A3-50-450. It has been noted that there is a tendency for the rate of increase in moment capacity to decrease as the thickness of the CFRP increases. The difference in the increase in the beam moment capacity is greater when the CFRP thickness changes from 3 mm to 5 mm compared to when the CFRP thickness changes from 5 mm to 7 mm. Based on the data acquired, the highest ratio of this difference (namely 2.3) is found for the use of 600 mm long CFRP. This length is equal to distance between two load points on the beam. Given these conditions, the authors believe that there is an optimum thickness for CFRP at which any further increase in that thickness will no longer significantly contribute to the increase in steel beam moment capacity.

3.2. CFRP's Elastic Modulus

The elastic modulus of CFRP determines the flexural rigidity of the strengthening system. The flexural rigidity of CFRP is a key factor in unbonded CFRP strengthening. The higher CFRP elastic modulus, the higher flexural rigidity of the strengthening. This condition is confirmed by the beam simulation results, as shown in Figure 10a. Unbonded CFRP with a modulus of elasticity of 200 GPa provides the highest strengthening effect in terms of increasing the initial stiffness of steel beams in this study, followed in turn by CFRP with a modulus of elasticity of 100 GPa and 50 GPa. There is a tendency for the rate of increase in the initial stiffness of the beam to become higher as the modulus of elasticity of the CFRP increases.

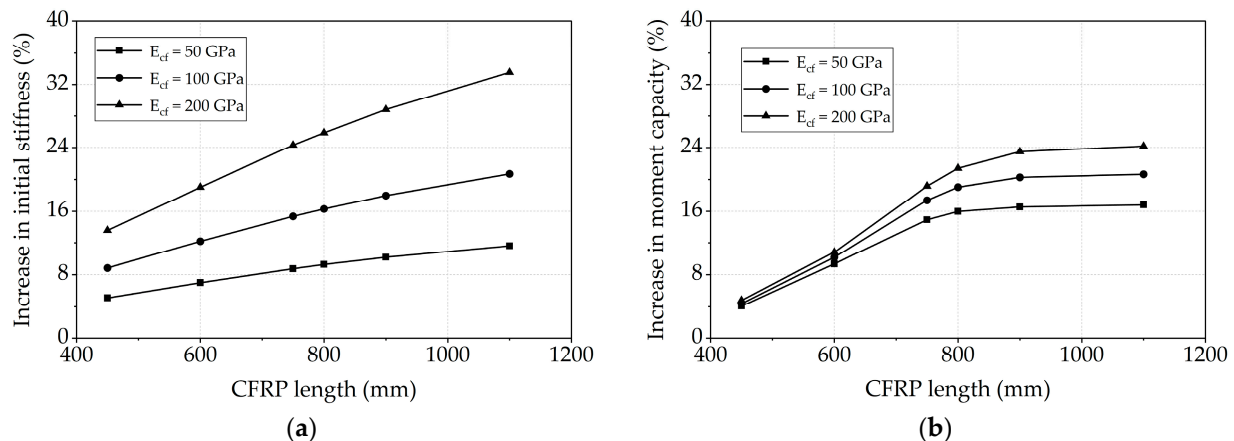


Figure 10. The effect of different CFRP elastic moduli on the performance of steel I-beams: (a) initial stiffness; (b) bending moment capacity.

The effect of CFRP elastic modulus on the moment capacity of the beams is shown in Figure 10b. Overall, the increase in moment capacity of steel beams ranges between 4.1% and 24.2%. As with the thickness of CFRP, a downward trend in the rate of increase in the moment capacity of steel beams is also confirmed as the modulus of elasticity of CFRP used increases. Unbonded strengthening does rely on the flexural rigidity of CFRP, which is determined by the elastic modulus and thickness of the CFRP, in contributing to the performance of steel beams. However, the downward trend in the rate of increase in moment capacity of the beam confirmed in this study cannot be separated from the effect of CFRP length. The CFRP length that is shorter than the total length or span length of the beam has shifted the failure mode of the beam to steel elements around CFRP ends. The higher flexural rigidity of CFRP leads to the failure mode in steel occurring much earlier before the CFRP reaches its maximum capacity. A large difference in the percentage increase in beam moment capacity is observed when the CFRP length is 750 mm, which is slightly higher than the distance between two loading points (600 mm). At this length (750 mm), a change in CFRP elastic modulus from 50 GPa to 100 GPa yields a difference in the percentage increase in beam moment capacity of 2.5%, while a change in the CFRP elastic modulus from 100 GPa to 200 GPa only gives a difference in the percentage increase in beam moment capacity of 1.8%.

3.3. Steel Section Types

Two types of beams, A and B, are employed in this study to examine the differences that arise. It can be seen from Figure 11a that there is almost no difference in the pattern of increasing initial stiffness of beams A and B as the CFRP length increases. However, the presence of CFRP provides a better effect on beam A compared to beam B. Using the CFRP with the shortest length, i.e., 450 mm, initial stiffness increased by 5.1% for beam A and

by 4.2% for beam B. The difference in percentage increase in the initial stiffness of these two beams is the highest (2.5%) when the CFRP length is 1100 mm. In this condition, the initial stiffness of beam B increases by only 9.1%, whereas that of beam A increases by 11.6%. The reason behind the large effect of strengthening on beam A is related to its lower initial stiffness (bare steel) compared to beam B, such that the contribution of CFRP strengthening becomes more 'real'. Beam A has a moment of inertia of only $13.18 \times 10^6 \text{ mm}^4$ while beam B has a moment of inertia of $44.76 \times 10^6 \text{ mm}^4$.

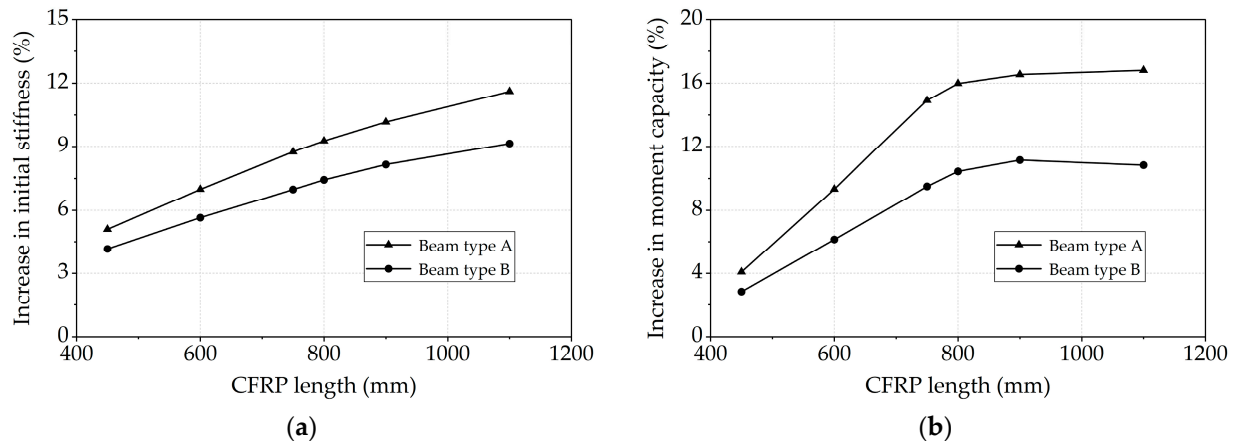


Figure 11. The effect of different steel I-beam cross-sections on the beam performance: (a) initial stiffness; (b) bending moment capacity.

Figure 11b presents a comparison of the increase in moment capacity between beam A and beam B for various CFRP lengths. It can be seen that a linear trend in the increase in moment capacity of the beams occurs only up to a CFRP length of 700 mm or 800 mm. The increase in moment capacity of beam A is also higher than that of beam B. The percentage increase in the beam moment capacity is 4.1% (beam A) and 2.8% (beam B) for using a CFRP length of 450 mm. This value increases to 16.0% (beam A) and 10.4% (beam B) for a CFRP length of 800 mm, and further increases to 16.8% (beam A) and 10.8% (beam B) for a CFRP length of 1100 mm. The higher increase in moment capacity of beam A compared to beam B is also due to the lower moment of inertia of beam A.

3.4. Strengthening Length

The effect of CFRP length on initial stiffness and moment capacity of the beams is shown in Figures 9–11. Moreover, it can also be seen from Figure 8 and Table 1. Based on Figures 9a–11a, the percentage increase in initial stiffness of steel beams increases as CFRP length increases with a nearly linear trend. This increase occurs at different rates that are influenced by the thickness of CFRP, the CFRP elastic modulus, and types of beam cross-section. The rate of increase in initial stiffness for beam type A is slightly higher than that of beam type B. The rate of increase in initial stiffness is also higher when using CFRP with greater thickness and modulus of elasticity. For example, on changing the length of CFRP from 450 mm to 1100 mm, the difference in percentage increase in initial beam stiffness is only 6.5% for using CFRP with an elastic modulus of 50 GPa. This value increases three times to approximately 20% for using CFRP with an elastic modulus of 200 GPa. One interesting finding is that a linear trend in the increase in beam moment capacity occurs only up to a certain CFRP length, i.e., approximately 700 mm (Figures 9b–11b). Beyond this length, the percentage increase in beam moment capacity does not show any significant change, or remain almost constant, until CFRP length reaches 1100 mm. This fact suggests that it is not necessary to use CFRP of the same length as the total length of the beam. This is an indication regarding the optimum length of CFRP for

unbonded strengthening of steel beams. The optimum length can be influenced by the position/distance between two loading points. However, this requires further investigation given that only one loading distance value is considered in this study.

3.5. Stress Distribution

A typical stress distribution in a steel beam strengthened with unbonded CFRP is presented in Figure 12. It can be seen from the figure that stress concentrations appear on the inner side of the CFRP ends and on the steel part at that position. This confirms that there is contact between the CFRP and steel. Further observation reveals that stress at this location develops more rapidly in beams using CFRP with higher flexural rigidity. Moreover, the rate of stress increase increases many times over after the steel beam passes through the yielding phase.

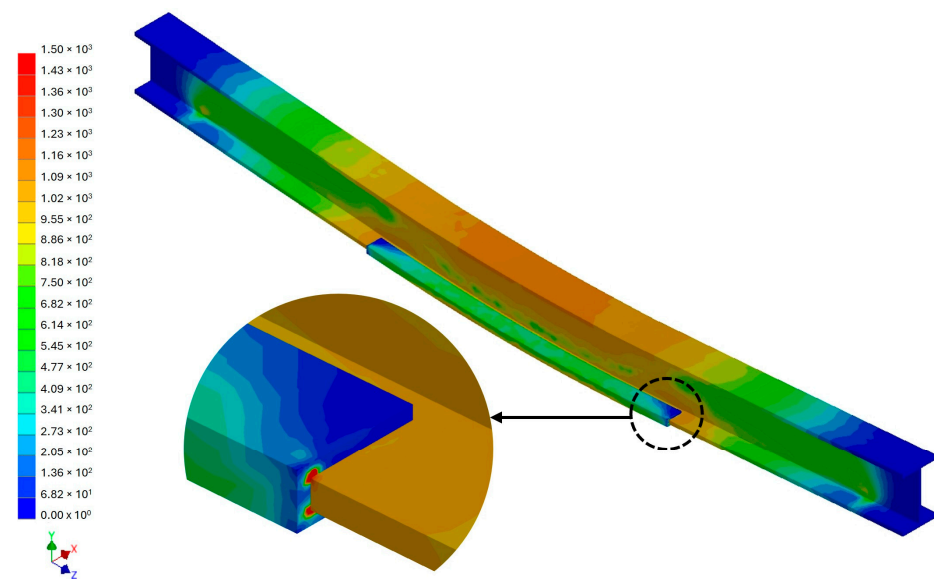


Figure 12. Stress distribution on steel I-beam strengthened with unbonded CFRP.

4. Conclusions

In this paper, a numerical study on the application of unbonded CFRP for strengthening steel I-beams is presented. A total of 38 finite element models is developed to explore the effect of several parameters—CFRP thickness, CFRP elastic modulus, type of steel beam cross-section, and strengthening length—on the initial stiffness and moment capacity of the steel beams. Some of the limitations of this study include isotropic assumption for CFRP, one type of loading configuration, and only two types of steel cross-sections being adopted. Fatigue loading, temperature effects, and long-term performance are not considered. Furthermore, no direct experimental validation is carried out for the beam's flexural strengthening configuration. Based on the investigation, the following conclusions can be drawn:

- Unbonded CFRP strengthening contributes positively to the initial stiffness and moment capacity of steel I-beams. The improvement in the beam performance is influenced by CFRP thickness, CFRP elastic modulus, type of steel I-beam cross-section, and strengthening length.
- The initial stiffness of the beam increases as the thickness of CFRP, CFRP elastic modulus, and strengthening length increase. The trend in the increase in initial stiffness is almost completely linear with the increase in strengthening length.
- The moment capacity of the beam also increases with increasing CFRP thickness, CFRP elastic modulus, and strengthening length. However, a linear trend in the percentage

increase in the beam moment capacity is only observed up to a CFRP length of 700 mm or 800 mm. Beyond this length, percentage increase in the beam moment capacity does not change significantly.

- Unbonded CFRP strengthening contributes more significantly to steel beams with a lower moment of inertia.

Given the limitations of this study, further investigation is needed to further explore the application of this strengthening system. Some areas of concern include issues such as beam failure mechanisms and optimal strengthening design criteria. Investigations can be conducted through both experimental and theoretical studies.

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