A novel mechanical clamp for strengthening of steel members using prestressed CFRP plates

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ABSTRACT: Strengthening of existing steel members using prestressed carbon fiber reinforced polymer (CFRP) plates has certain advantages over non-prestressed reinforcement, especially due to the reduction in permanent tensile stresses acting on the steel members. However, only very low prestressing levels in CFRP plates may be reached when adhesively-bonded reinforcement is used. The reason is that high interfacial shear stresses generated in the adhesive layer during the prestress release process lead to the premature debonding of the prestressed CFRP reinforcements from the steel substrate under transient service loads. In the current study, a novel unbonded mechanical clamp is proposed to anchor high prestressing forces to the steel substrate. A finite element (FE) model was used to optimize the design of the required mechanical parts. Subsequently, a set of static and fatigue tests was performed to evaluate the performance of the optimized system. The experimental results proved that the proposed system is capable of transferring the entire tensile capacity of the normal modulus CFRP reinforcing plates (50 × 1.4 mm each) to the steel substrate without any slippage of the joint. Consequently, based on the static and fatigue tests performed in the current study, it can be concluded that the proposed unbonded mechanical clamping system can be used for strengthening of existing steel structures using prestressed unbonded reinforcements (PURs) to increase the ultimate capacity and/or fatigue life.

1 INTRODUCTION

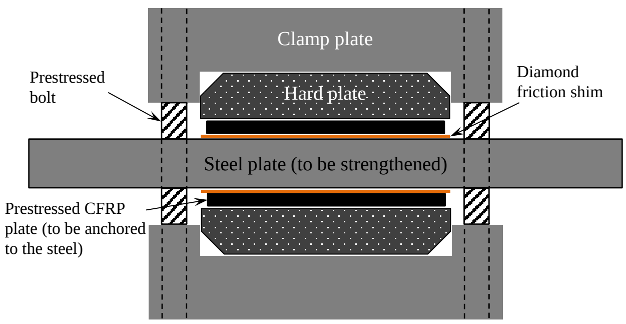
Today, a large number of existing metallic structures need to be strengthened against fatigue to carry higher service loads and/or be sufficiently safe for a longer service life. The unique advantages of carbon fiber reinforced polymer (CFRP) composites, such as high corrosion resistance, light weight, high strength and fatigue endurance, have made CFRP composites a well-accepted material for static and fatigue strengthening of such structures (Zhao 2013). Although it is evident that the utilization of prestressed CFRP composites has several advantages over nonprestressed reinforcement due to their ability to reduce permanent tensile stresses in the member, few attempts have been made to use prestressed bonded reinforcement

(PBR) systems for strengthening of steel members in practical cases (see Koller et al. 2012). This may be explained by the fact that high prestressing levels cannot be reached in bonded CFRP reinforcement, due to their premature debonding. Consequently, in order for PBR systems to be effective, the high interfacial and peeling stresses generated in the end zones of the prestressed reinforcement laminates should be avoided. Therefore, as a typical solution dealing with debonding failure of PBRs, mechanical end-anchorages are commonly used, while very few laboratory applications of PBR systems without any end-anchorages can be found in the literature (Ghafoori et al. 2012; Nakamura et al. 2014; Emdad and Al-Mahaidi 2015). Furthermore, either non-prestressed or prestressed adhesively-bonded CFRP-to-steel joints have some disadvantages, including the time-consuming and costly surface preparation procedure, and durability concerns.

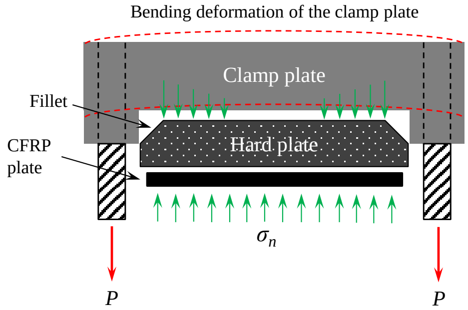
As an alternative to the PBR solution, a prestressed unbonded reinforcement (PUR) system has recently been proposed for the fatigue strengthening of steel I-beams using mechanical end anchorages (Ghafoori and Motavalli 2015). In the current study, a novel mechanical clamping system has been developed and tested under static and fatigue loading, which can be used for static/fatigue strengthening of tensile steel members using prestressed CFRP plates. The performance of the proposed system was investigated in a set of static tests performed on steel plates strengthened with conventional PBRs and the proposed PUR system. It should be mentioned that the current paper summarizes one part of a large research program on fatigue strengthening of metallic members using CFRP composites at the Swiss Federal Laboratories for Materials Science and Technology (Empa) in collaboration with the Swiss Federal Institute of Technology, Lausanne (EPFL), and Monash and Swinburne Universities in Melbourne.

2 DESIGN BASIS OF THE PROPOSED MECHANICAL CLAMP

A schematic cross-sectional view of the proposed mechanical anchorage system is illustrated in Figure 1a. As the figure shows, the main idea of the system is to hold the prestressed CFRP plates on the steel member (the steel plate in this case) with the help of friction. Therefore, it is necessary to press the prestressed CFRP plates against the steel member using prestressed bolts. As the system functions with friction, 3M^{TM} diamond friction shims (3M Technical Ceramics GmbH, Germany) can be used between the CFRP plates and the steel substrate to increase the friction. Consequently, having an idea regarding the static friction in CFRP-diamond shim, and diamond shim-steel interfaces, the required prestressing force which should be provided by prestressed bolts can be calculated for a target value of axial stress in the CFRP plates (herein the ultimate tensile capacity).



(a)



(b)

Figure 1. Schematic view of the mechanical clamping system: (a) cross-sectional view; (b) stress transfer between different parts.

Due to the bending deformation of the clamp plate upon fastening the prestressed bolts (see Figure 1b), it is clear that another mechanical part, called the *hard plate*, is needed to transfer the lateral compression force from the clamp to the CFRP plate through a more uniform distribution, σ_n, and avoid pinching of it. The hard plates are toothed on the contact side with the CFRP and they have a hardness of HRC 58(-60) on the Rockwell scale. It is obvious that the fillet dimension of the hard plate (see Figure 1b) is one of the most important parameters affecting the contact stress distribution. Due to the complexity of the system a finite element (FE) simulation has been performed to optimize the dimensions of the different mechanical parts.

3 FE SIMULATION

3.1 *Model description*

Due to the symmetry, a finite element (FE) model of one fourth of the proposed mechanical clamps was assembled in ABAQUS (2014) (Figure 2). The FE model consisted of a CFRP plate (50 × 1.4 mm) pressed against the steel substrate via the mechanical clamp (see Section 4.1 for the dimensions). All the steel parts and the CFRP plate were modelled as isotropic linear elastic materials with an elastic modulus of 200 and 170 GPa, respectively, and a Poisson's ratio of 0.3. A hard contact was used between the clamp plate, hard plate, CFRP, and the steel substrate in the normal direction. However, using the penalty formulation, an isotropic tangential friction was introduced between the CFRP plate and the steel substrate with a friction coefficient of μ_s = 0.3. The CFRP and the steel substrate were modelled using 8-node linear brick elements of type C3D8R with reduced integration and hourglass control, while the hard plate and the clamp were modelled using a 10-node quadratic tetrahedron of type C3D10. In the first stage, a static uniform pressure of 396 MPa per bolt location was introduced on the clamp plate to simulate the prestressing force of 72 kN per bolt, generated in M12 high-strength bolts upon fastening with an allowable torque of 160 N·m. In the next stage, a uniform displacement-controlled loading was applied to the free edge of the CFRP plate to evaluate the anchorage capacity of the joint before slippage of the CFRP. The FE model was generated firstly to check the stresses in the clamp plate and optimize its thickness; and secondly, to perform a parametric study to optimize the fillet dimension of the hard plate to obtain an approximately uniform contact pressure between the hard plate and the CFRP strip.

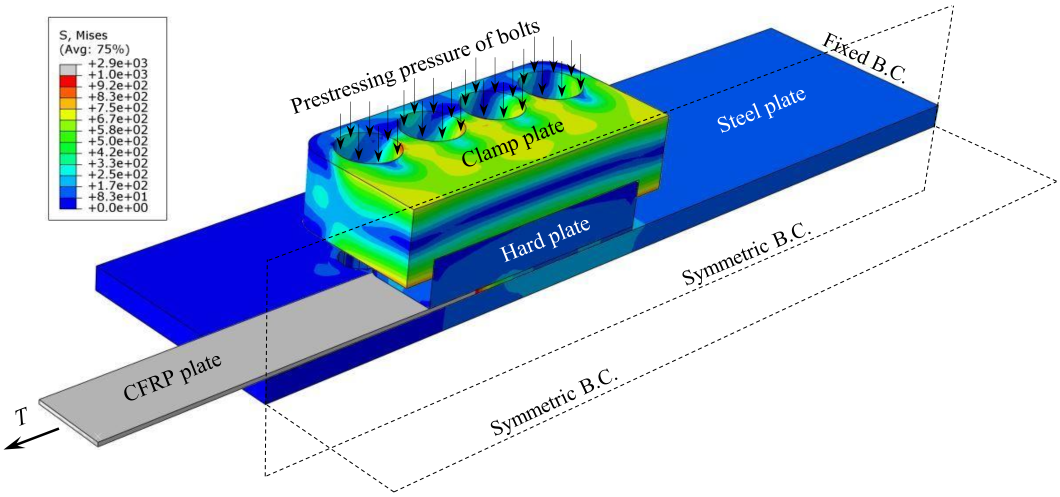
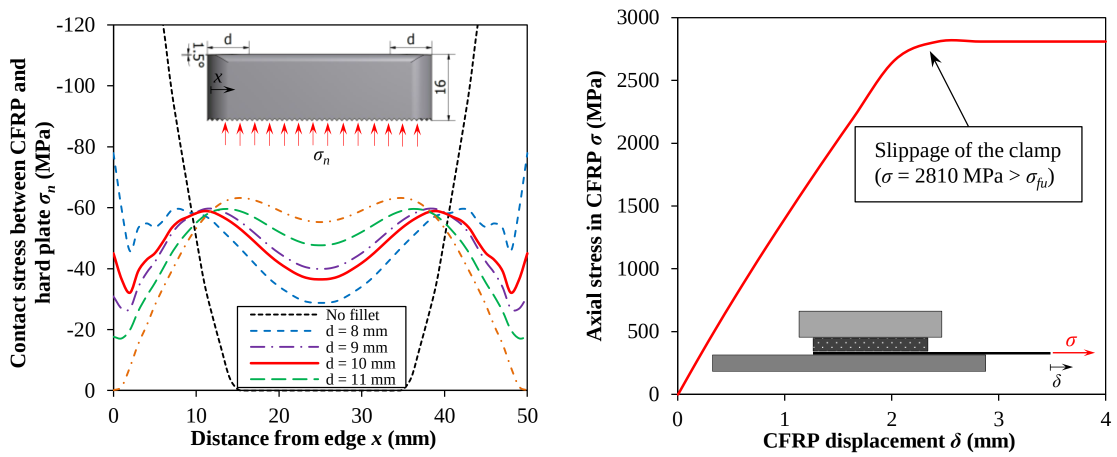


Figure 2. ABAQUS model of the mechanical clamping system for unbonded CFRP-to-steel joints.

3.2 *FE results*

Figure 2 shows the von Mises stresses in the FE model when the full bolts load is applied on the clamp plate, and the CFRP plate is pulled up to its tensile strength. It can be seen that by using 25 mm-thick clamp plates manufactured from M200 steel with a nominal yield strength of 1000 MPa, the maximum stress in the clamp plate is below 0.6 f_y. Moreover, Figure 3a illustrates the effect of the hard plate fillet dimensions on the distribution of the contact pressure between the hard plate and the CFRP strip. It can be seen from the figure that having no fillet results in a singular stress concentration on the CFRP edges, while there is no contact pressure in the middle width of the CFRP plate. The parametric study demonstrated that using a fillet dimension of 10 mm with an angle of 1.5° is the optimal configuration for the hard plate to reach a more uniform contact pressure on the CFRP plate. Note that round fillets with a radius of 2 mm were also considered in the longitudinal direction to avoid stress concentration.

Using the optimized FE model of the mechanical clamps, the stress–elongation response of the CFRP plate was obtained and is provided in Figure 3b. It can be seen from the figure that the proposed mechanical clamp is capable of carrying the entire tensile capacity of the CFRP plate (σ_{fu} = 2600 MPa) before any slippage of the clamp. It is obvious that the ultimate capacity of the proposed anchorage system is a function of μ_s between the CFRP plate and the steel substrate. It has been demonstrated by Ghafoori (2015) that μ_s = 0.5 can be reached by using a diamond friction shim. Therefore, it can be concluded that by considering μ_s = 0.3, the ultimate capacity of the designed system obtained from FE modeling is indeed on the safe side.



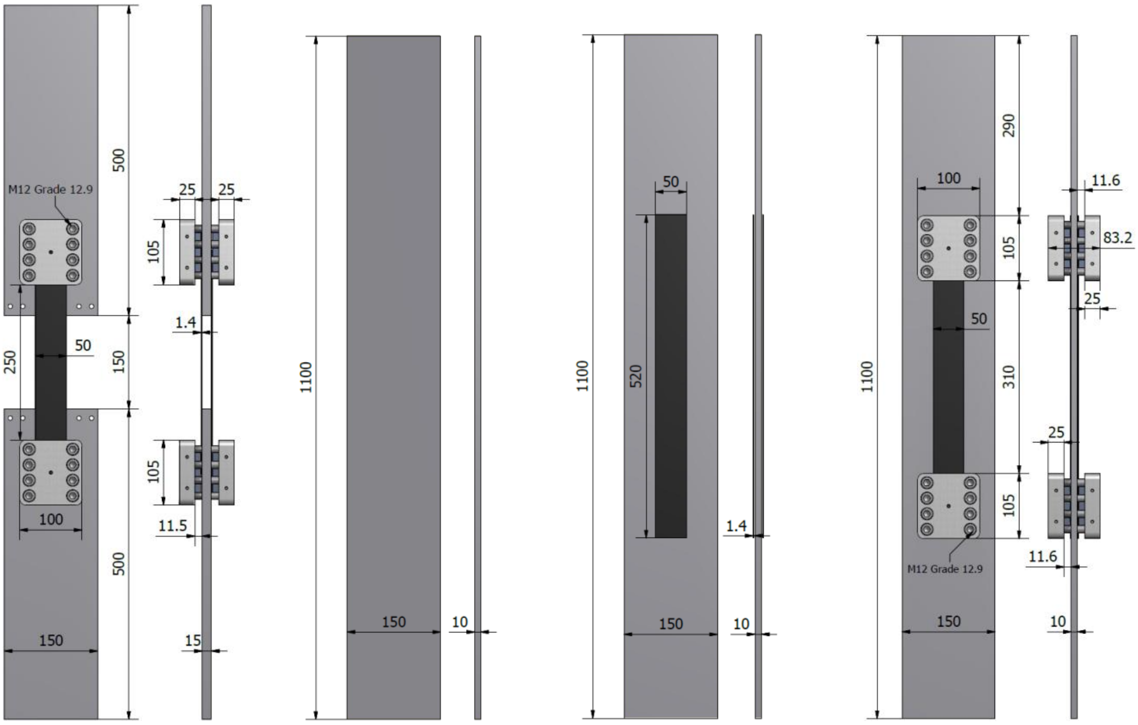
(a) (b)

Figure 3. FE results: (a) effect of fillet dimension on the distribution of the contact pressure (d = fillet dimension); (b) ultimate capacity of the joint before slippage of the clamp.

4 EXPERIMENTAL VERIFICATION

4.1 *Test specimens*

To evaluate the performance of the proposed mechanical clamping system for the fatigue strengthening of tensile steel members, two sets of tensile tests were carried out. The first set of experiments was performed on tensile specimens, as depicted in Figure 4a, to evaluate the ultimate capacity and fatigue performance of the mechanical clamps. In the second set of static tensile tests on steel plates (see Figure 4b-d), the performance of the PUR system consisting of the proposed mechanical clamps, was compared to that of the PBR solution.



(a) Clamp test specimen (b) Reference specimen (c) PBR specimen (d) PUR specimen

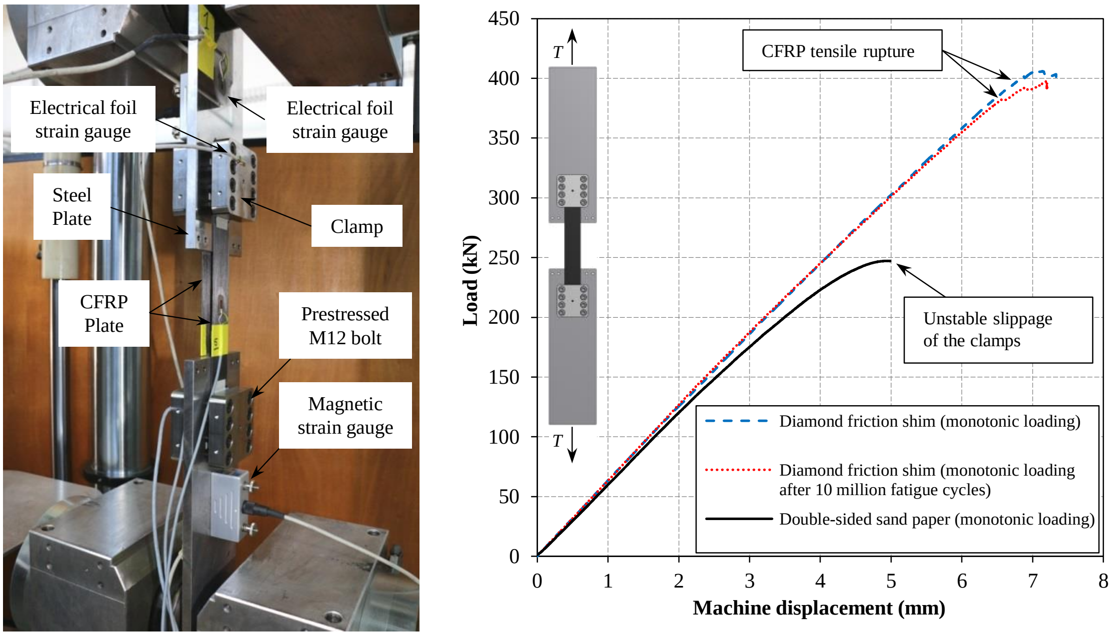
Figure 4. Tensile test specimens (all dimensions are in mm).

4.2 *Material properties*

With the exception of the mechanical parts of the proposed clamping system, which were made from high strength M200 steel, the utilized steel plates in all the experiments was of type S355J2+C with a nominal yield strength of 355 MPa. The Young's modulus of the steel was found to be 200.9 GPa in the reference static test (Figure 4b). Moreover, normal modulus CFRP plates of type S&P 150/2000 with measured cross-sectional dimensions of 50 × 1.4 mm (width × thickness) were used in all the tests. The tensile strength of the CFRP material utilized was 2530 MPa, while the elastic modulus was 156 GPa (Hosseini et al. 2016).

4.3 *Test setup*

A 1-MN static/fatigue servo-hydraulic Schenck machine with an Instron controller was used to perform the static and fatigue tensile tests. All the static tests were performed under displacement-control conditions at a speed of 1 mm/min. Fatigue tests on clamps were performed under the load-control condition with a load ratio of R = 0.9, and a frequency of 15 Hz. The maximum load level during the fatigue test on the mechanical clamp specimen (Figure 4a) was equal to T_{max} = 124 kN, which corresponded to 35% of the ultimate tensile strength of the utilized CFRP. Figure 5a shows the test setup and the instrumentation used to monitor the specimens during the static and fatigue testing.



(a) (b)

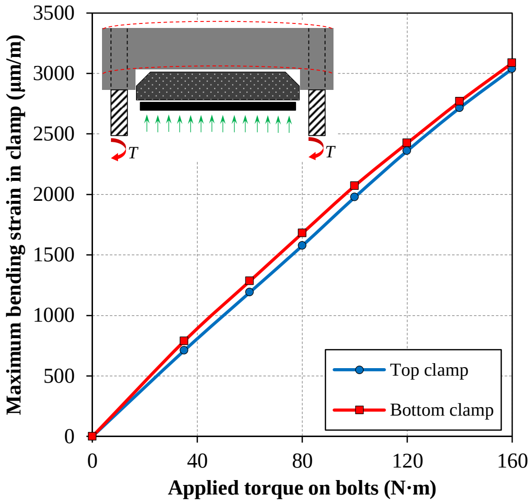
Figure 5. (a) Test setup for static and fatigue tests; (b) load–displacement response of clamp test specimens.

5 EXPERIMENTAL RESULTS AND DISCUSSION

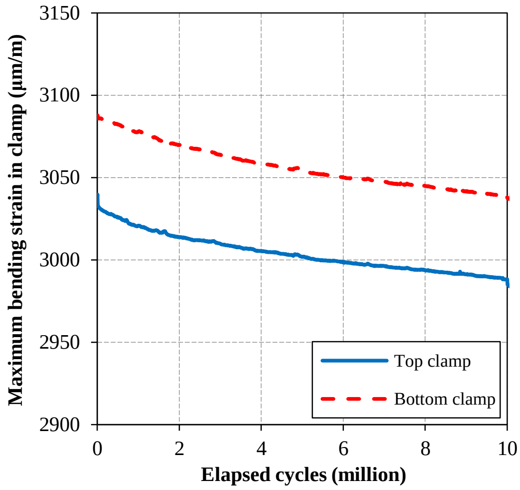
5.1 *Static and fatigue tests on the proposed mechanical clamping system*

Figure 5b illustrates the load-deformation of the three clamp test specimens. It can be seen from the figure that when double-sided sand paper was used between the CFRP plate and the steel substrate, the friction joint behaved relatively softer, while at 60% of the ultimate tensile capacity of the CFRP plates, the stiffness of the joint was almost zero and unstable slippage of the system occurred. On the other hand, when diamond friction shims were used to increase the friction in the joint, no reduction in the joint stiffness or slippage of the clamps was observed until tensile rupture of the CFRP plates occurred. The third clamp test specimen was first subjected to 10 million fatigue cycles with T_{max} = 124 kN and R = 0.9. Afterwards, a static loading was applied on the mechanically-anchored CFRP plates until the ultimate strength of the CFRP plates was reached. Consequently, the experimental results obtained from the clamp test specimens demonstrated that the proposed mechanical clamps are capable of transferring the entire tensile capacity of the CFRP plates to the steel substrate, even after experiencing 10 million fatigue cycles.

The maximum bending strain generated in the mechanical clamps is plotted against the applied torque on the eight M12 (grade 12.9) bolts of the system in Figure 6a. A comparison of the experimental values provided in Figure 6a with the FE results presented in Figure 2 reveals that a good correlation exists between the experimental and FE results of the maximum bending stress in the clamps. Moreover, the maximum strain level in the clamp plates was monitored during the 10 million fatigue cycles (Figure 6b), which revealed that the maximum bending strain in clamp plates was reduced by about 1.5% over 10 million fatigue cycles. This means that the prestressing force in M12 bolts was reduced by 1.5% over 10 million fatigue cycles, which deemed to be an acceptable value for the proposed mechanical clamping system.



(a)



(b)

Figure 6. (a) Maximum bending strain in clamp plates versus applied torque; (b) evolution of maximum bending strain in mechanical clamps with respect to fatigue cycles.

5.2 *Static tests on prestressed CFRP-strengthened steel plates*

In the second series of experiments, the performance of the proposed PUR system was compared with that of the PBR solution using static tensile tests on steel plate specimens (Figure 4b-d). With the exception of the reference specimen, which was tested without any external CFRP strengthening, two prestressed CFRP plates with an initial prestressing force of 60 kN per CFRP plate were used in both the PBR and PUR specimens (see Hosseini et al. 2016 for the prestressing procedure). All the specimens were subjected to uniaxial tensile loading up to a load level equal to 500 kN, which was lower than the yield strength of the bare steel.

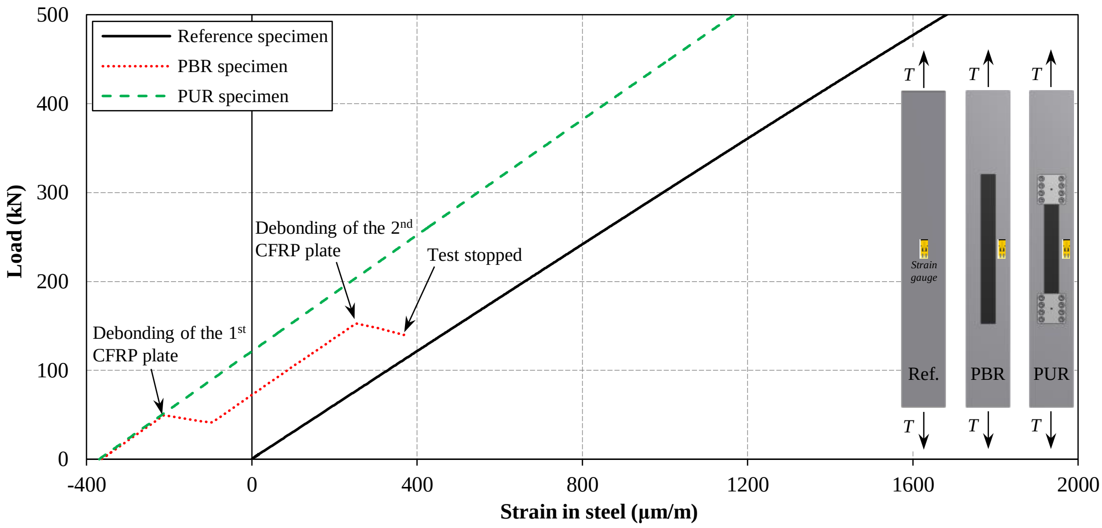


Figure 7. Load–strain response of the unstrengthened and CFRP-strengthened steel plate specimens.

Load–strain responses of all the tested specimens are provided in Figure 7. Compared to the reference specimen, strengthening of the steel plates using PBR or PUR slightly increased the stiffness of the member within the strengthened length. However, Figure 7 clearly shows the great advantage of using prestressed CFRP reinforcements in reducing the tensile strain level in the steel member under external loading. The experimental results revealed that the prestressed bonded CFRP plates in the PBR specimen were debonded from the steel plate at considerably low load levels, while the mechanical clamps could carry the prestressing force up to the end of the loading procedure without experiencing any slippage (Figure 7).

6 SUMMARY AND CONCLUSIONS

In the current study, a novel friction-based mechanical clamp for strengthening of tensile metallic members with prestressed CFRP plates was designed, manufactured, and tested under static and fatigue loading. Experimental results revealed that the proposed clamps are capable of transferring the entire tensile capacity of the CFRP plates to the steel substrate, even after experiencing 10 million fatigue cycles. The comparative performance of the clamps was further investigated in a set of static tests on steel plate specimens strengthened with the PBR and PUR systems. The experimental results showed that, even though the adhesive bonding can transfer the prestressing force to the steel substrate, the available capacity of the PBRs is relatively low for transferring the external load into the system. Due to the advantages of the PUR system, including its ease of application, elimination of any surface preparation, and the high performance of the system in terms of prestressing levels, the proposed PUR system can be used as an alternative to PBR solutions for static/fatigue strengthening of existing steel structures.

7 ACKNOWLEDGMENTS

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