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Structural Evaluation of Reinforced Concrete Beams Retrofitted using Cold-Formed Steel Plates

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ABSTRACT Shear strengthening of reinforced concrete (RC) beams has become increasingly important for improving the safety and durability of existing structures. Existing studies focus on the use of materials such as Fiber Reinforced Polymer (FRP) and bonded steel plates. The use of cold-formed steel plates as retrofitting material in reinforced concrete beam remains limited; thus, this study focuses on the behavior of RC beams strengthened using cold-formed steel plates installed diagonally at a 45-degree angle and bonded with epoxy adhesive. Two beam specimens with dimensions of 250 × 400 × 1500 mm were evaluated through three point bending test: a control beam (B0) without strengthening and a strengthened beam (B1) with a single cold-formed steel plate bonded to the beam web. The load was applied under quasi-static monotonic loading using a load-controlled protocol, where the deflection was monitored by Linear Variable Differential Transformer (LVDT) placed at midspan, ¼ span, and ¾ span. Test results showed that the initial yielding load for the control specimen B0 was 283.07 kN, while the strengthened specimen B1 yielded at 288.91 kN, indicating a 2.44% increase in initial yield load due to the presence of the cold-formed steel plate. Loading was continued up to 350 kN, at which point the midspan deflection of B0 was measured at 21.40 mm, whereas B1 exhibited a lower deflection of 17.81 mm, demonstrating improved stiffness and reduced deformation. The study confirms that retrofitting RC beams with diagonally installed cold-formed steel plates can effectively enhance their shear capacity and stiffness, especially in the early stages of the loading phase. Cold-formed steel plates can also prevent early shear cracks propagation in the beam. This strengthening technique offers a practical and efficient method for extending the service life of existing concrete structures.

KEYWORDS Beam Strengthening; Cold-Formed Steel, External Retrofitting, Shear Strengthening

1 INTRODUCTION

Reinforced concrete structures are among the most widely used in the construction sector. History shows that the earliest use of concrete structures was recorded in 6500 BC in Syria and Jordan. The extensive use of concrete structures is reflected in data showing that cement consumption in global industry continues to increase annually (Volume Concrete, 2025). Reinforced concrete structures provide strength, durability, and fire resistance; therefore, this material remains as the primary choice in the construction industry. However, throughout the concrete structures service life, they are susceptible to strength degradation induced by aging, overloading, or seismic activity. Damage to concrete beams can be more severe when the beams are subjected to sustained loading and exposed to several corrosive agents such as acid-salt mist, carbon dioxide, and variation of temperature, and humidity (Li et al., 2022). Thus, repair and retrofit of concrete structures remain common issues among global academic researchers. Repair and retrofit can be done by jacketing technique-where an additional layer of materials is applied around the reinforced concrete surface – or by wrapping, where an additional sheet material is bonded and attached to the surface of the concrete structure. Li et al. (2022) conducted shear strengthening of reinforced concrete beams using High Tensile Strength Strain Hardening Cementitious Composites (HTS-SHCC) and Ultra-High-Performance Concrete (UHPC) through jacketing technique, showed that shear capacity of the beam increased by 53.2% to 83.2% and failed due to shear detachment. Furthermore, incorporating recycled tire steel fiber into the high strength concrete during concrete structure jacketing has also been shown as an alternative to enhance the concrete capacity as conducted by Alasmari et al. (2025).

The use of Fiber Reinforced Polymer (FRP) is a favorable practice for concrete structures enhancement through wrapping technique. Fiber reinforced polymer provides several advantages, including corrosion resistance, high longitudinal tensile strength, and easy installation (Siddika et al., 2019). Despite its advantages, the application of FRP as reinforcement involves considerable cost. As an alternative, aluminum alloy, strands, as well as steel plates may be utilized for reinforced concrete strengthening. Abdalla et al. (2016) used externally bonded aluminum alloy plates to strengthen existing reinforced concrete beams, showing that the shear capacity increased by 24% to 89% with the 45°- oriented aluminum plates proving to be the most effective. Application of Near Surface Method (NSM) using aluminum alloy bar as flexural strengthening in reinforced concrete beams has also been investigated, where the existing concrete beams were grooved and filled with epoxy and aluminum bars. Inserting aluminum alloy plates can significantly increase the first crack load of the beam by 44% to 111%, as well as it yield load increased by 13% to 30% (Xing et al., 2020). However, important notes on the NSM methods were revealed by Yu et al. (2020), where the deflection of the strengthened beams was obviously decreased even though the load bearing capacity increased, resulting in the lower ductility level. To address this, CFRP jacketing at the end of aluminum alloy bar NSM zone can be applied to improve the deformation and ductility capacity.

While attaching aluminum alloy can improve both shear and flexural capacity of the existing reinforced concrete beams, the use of non-prestressed strands bonded to reinforced concrete beams does not have significant effect on their structural capacity. The use of externally bonded vertical non-prestressed strands as shear reinforcement only increases the existing beam shear capacity by approximately 25% to 35% (at yield) and 3% to 8% (at ultimate) (Susanto et al., 2022). Moreover, the flexural capacity of the strengthened beam was 12%-33% higher than that of unstrengthen beam (Iswanto et al., 2021). A higher improvement in flexural capacity, 26% at yield and 72% at ultimate – was achieved when the strands were applied using anchorage system (comprising a steel plate and dynabolt) and covered by mortar adhesive (Atmajayanti et al., 2025). However, the flexural capacity of the strengthened beam was 12%-33% higher than that of unstrengthen beam (Iswanto et al., 2021).

Inserting steel plates into the reinforced concrete beam can increase their capability to resist flexure and shear. Alasadi et al. (2020) placed steel plates on top of over-reinforced concrete beams, mounted by bolts. This modification resulted in a 246% to 544% increase in the load at the first crack and shifted failure mode of the beams from brittle failure to flexural failure, followed by steel plates yielding. In addition, when steel plates were placed along both sides of the beam, the flexural capacity increase by 6-28% and affected the beam crack pattern (Thamrin and Sari, 2017). However, despite the increase capacity of the bonded steel strengthened beams, the potential reduction of strength may be considered as a notable drawback (Ozbek et al., 2016; Rakgate and Dundu, 2018). Another important issue is that insufficient epoxy bonding strength can result in earlier yielding of the steel plates (Ozbek et al., 2016). Another method for attaching steel plates to reinforced concrete involves the use of bolted connections. This method was employed by Sudarsana et al. (2019), who attached U-shaped and L-shaped steel plates onto reinforced concrete beams near the supports, securing them with bolted connections. The results depicted that beam reinforced with U-shaped steel plates exhibited greater stiffness compared to those with L-shaped plates prior to crack initiation. However, following the appearance of cracks, the stiffness of both configurations became relatively comparable.

Beyond the use of the conventional steel plates, cold-formed steel may also serve as an alternative material for concrete beams strengthening. Cold-formed steel is relatively lighter than hot-rolled steel and is fast and easy to install. Inserting cold-formed steel plates on the bottom sides of the concrete beams can raise the flexural capacity by 11% to 80% (Susanto et al., 2023). The ultimate stiffness of the beam strengthened with cold-formed steel also increased quite significantly (Puluhulawa et al., 2024). Furthermore, Raj et al. (2020) placed cold-formed steel partially in shear area and maximum bending area, and found that the thinner plates inserted on the beam resulted in higher capacity and ductility. In terms of shear capacity, placing cold-formed steel plates around reinforced concrete beams sides can increase the beams capacity by 16% (Puluhulawa et al., 2022). In contrast, applying cold-formed steel plates vertically along both webs of concrete beams induces higher increase in capacity - approximately 32% (Susanto et al., 2024). Crack caused by shear commonly appears diagonally on the beams, forming 45-degree angle with the longitudinal beam axis. Thus, installing external shear reinforcement perpendicular to the shear crack pattern line can effectively optimize shear capacity. Research related to the use of cold-formed steel plates as retrofitting material in reinforced concrete beam remains limited. Therefore, this paper investigates the structural capacity of the reinforced concrete beams retrofitted with diagonally installed bonded cold-formed steel. The beams were evaluated through three-point bending test, with a centered point load applied in the middle of the beam. The structural response of the beam, including stiffness and crack pattern occurred on the specimens were observed and compared with one another to evaluate the influence of the attached cold-formed steel plate on the reinforced concrete beams. The results of this study offer an easy and economical strengthening alternative due to the use of inexpensive and readily available materials.

2 METHODS

This research employed an experimental methodology, as described in Figure 1. In the early stages, all materials including concrete, reinforcement bars, as well as the cold-formed steel plates were prepared. This was followed by the specimen fabrication and material tests. During the final stage, the beam was subjected to loading test. The test result were then analyzed.

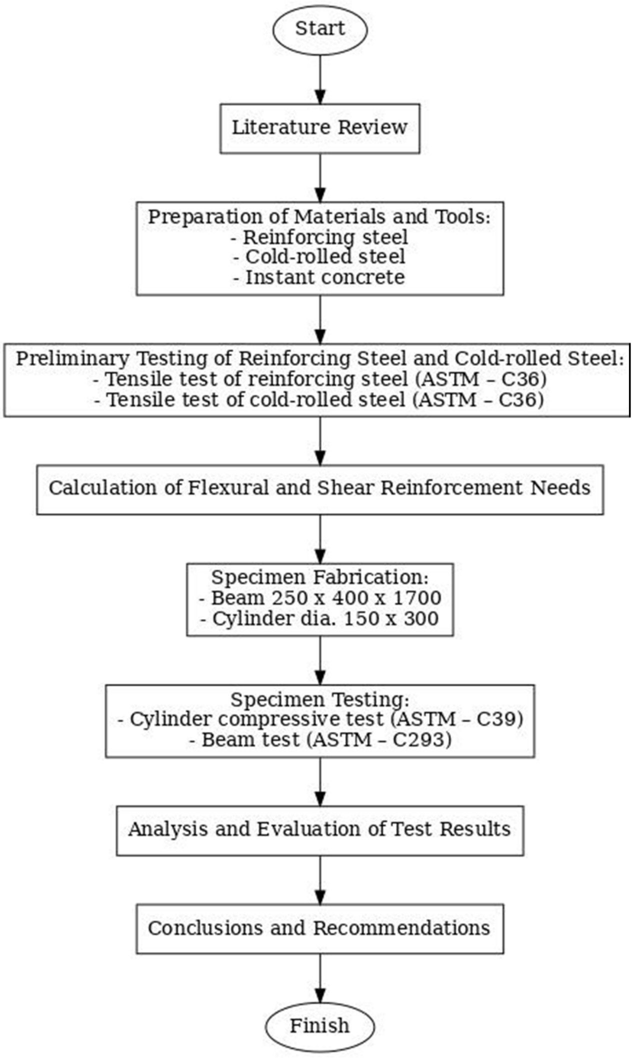


Figure 1. Research Flowchart.

2.1 Materials

Two (2) reinforced concrete beams were evaluated in this study. Pre-mixed concrete was used in the study. Three (3) concrete cylinder samples were created, with a diameter of 150 mm and a height of 300 mm. Following this, the compressive strength test in accordance with ASTM C39 was conducted. The result shows that the average compressive strength of the concrete samples was 46.2 MPa.

In addition to this, both shear and flexural reinforcement were provided in both beams. Three samples of the reinforcing bars were subjected to tensile strength test following ASTM C36. The average yield stress of the reinforcing bars was 377.99 MPa, while the average ultimate stress was 527.98 MPa. Furthermore, the yield and ultimate stresses of cold-formed steel were 563 MPa and 576 MPa, respectively.

2.2 Beam Specimen

Two (2) rectangular beam sections with dimensions of 250 × 400 mm were developed during this study. Both beams had a clear span of 1500 mm. Although the beam was tested at full scale, its span was intentionally reduced to induce shear failure prior to bending. Two flexural reinforcing bars with diameter of 13 mm were placed at the top of the beam, and six (6) of the same size were arranged at the bottom. The shear reinforcement, 6 mm diameter stirrups was applied having uniform spacing of 150 mm along the span, as presented in Figure 2 and Figure 3. The specimens were fabricated and named as B0 and B1, with the following descriptions:

1. One (1) rectangular reinforced concrete beam without strengthening (B0), serving as a reference (control specimen), as presented in Figure 2.
2. One (1) rectangular reinforced concrete beam strengthened with a single layer of cold-formed steel plates attached on both sides of the web of the concrete beam (B1). The cold-formed steel plates were attached using epoxy adhesive. An illustration can be seen in Figure 3. The cold formed steel 50 mm in width, and 250 mm in length. The thickness of the cold-formed steel plates was 0.7 mm, placed in quarter span of the beam. Cold-formed steel plates were placed at 45° inclined angle to achieve optimum strengthening effects, similar to the research findings of Thamrin et al. (2019), which showed that inclined CFRP sheet reinforcement yielded higher performance values compared to vertical installation.

Both specimens B0 and B1 were cured for a minimum of 28 days to maintain the temperature and moisture level of the concrete specimens. For specimen B1, the cold-formed steel reinforcement was attached after 28 days. Figure 4 shows the specimen B1 after the curing treatment was completed.

The beam tested in this study was designed in accordance with SNI 2847-2019 - Requirements for Struc-

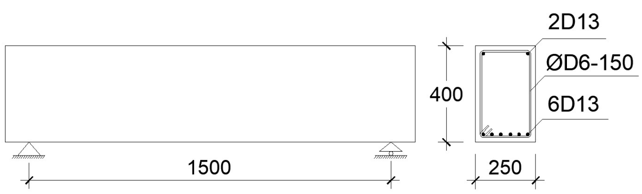


Figure 2. The cross-section of unstrengthened beam specimen, B0 (units in mm).

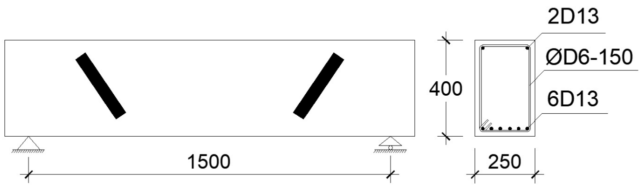


Figure 3. The cross-section of strengthened beam specimen, B1 (units in mm).

Figure 4. Beam Specimen.

tural Concrete in Building Construction (Badan Standardisasi Nasional, 2019). The flexural capacity was calculated using balanced strain compatibility principle as presented in Figure 5. In Equation (1), M_n is the flexural resistance (Nmm), a is the height of the stress block (mm), f'_c refers to concrete compressive strength (MPa), and b is the beam width (mm). d and d' denotes the distance from the concrete top surface to the centroid of the top and bottom reinforcing bars (mm). Furthermore, A'_s and f_s are the area (mm^2) and the actual stress (MPa) of the top longitudinal rebar.

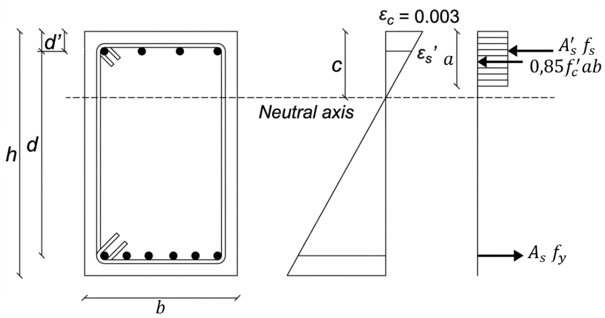


Figure 5. Strain compatibility and stress resultants diagram of reinforced concrete beam.

$$M_n = (0.85 f'_c ab) \times \left(d - \frac{a}{2}\right) + A'_s f'_s \times (d - d') \qquad (1)$$

Shear capacity of the reinforced concrete beam was calculated using Equation (2) to (4). V_n is the total shear resistance of the reinforced concrete beam obtained from the shear resistance of the concrete (V_c) and stirrups (V_s). Furthermore, b_w refers to the web width (mm), d refers to the effective depth (mm), A_v is the transverse reinforcement area (mm^2), f_{yt} is the yield stress of the transversal reinforcing bars (MPa), and s is the stirrups spacing (mm). Shear and moment capacities of the beam were then tabulated in Table 1.

$$V_n = V_c + V_s \qquad (2)$$

$$V_c = 0.17\sqrt{f'_c} b_w d \qquad (3)$$

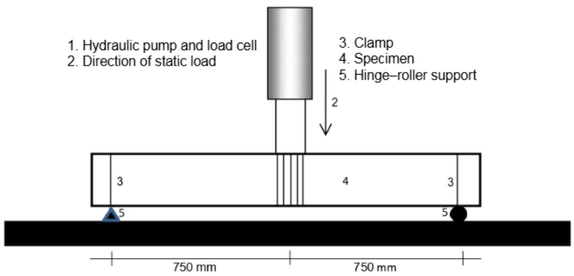
$$V_s = \frac{A_v f_{yt} d}{s} \qquad (4)$$

Table 1. Shear and Moment Capacity of Unstrengthened Beam

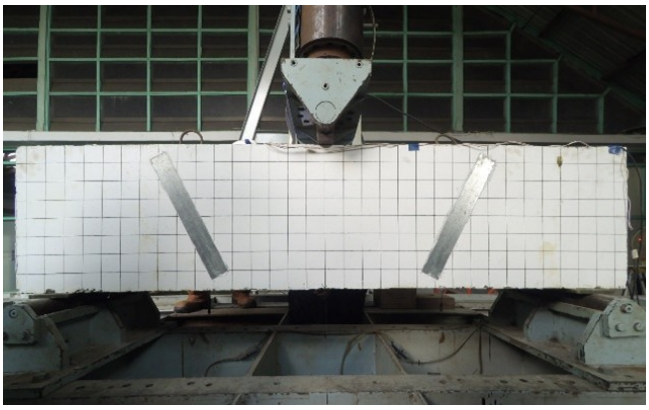
		Equivalent mid-span point load
Nominal shear, V_n	139.41 kN	278.82 kN
Nominal moment, M_n	105.93 kN	282.48 kN

2.3 Three Point Bending Test

The beam specimens were subjected to three point bending test, loading at their midpoint, following ASTM C293. The loading configuration of the beam is presented in Figure 6. Hydraulic pump and load cell were placed in the middle of the beam to distribute the applied load from the loading machine to



(a)



(b)

Figure 6. Three Point Bending Test setup Configuration: (a) schematic setup, and (b) laboratory test set up.

the beam specimen. The loading applied in this study was concentrated static load, with load-controlled protocol used since the beam response was within the elastic linear phase. As the beam transitioned to the plastic phase, the displacement-controlled protocol was employed. The data were recorded using data logger.

Several types of data were collected during the loading test. The deflection of the beam was measured at the ¼ span, mid-span, and ¾ span of the beam using Linear Variable Differential Transformer (LVDT). The location of each LVDT is described on Figure 7.

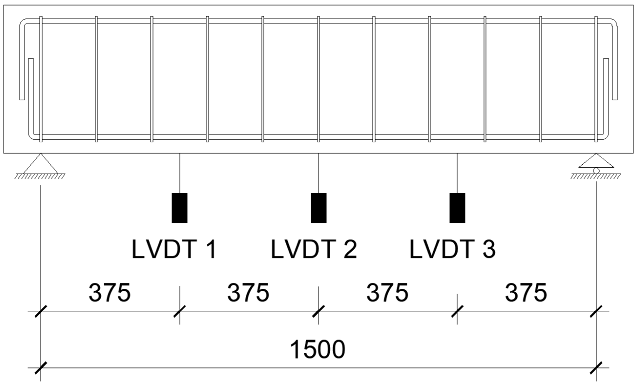


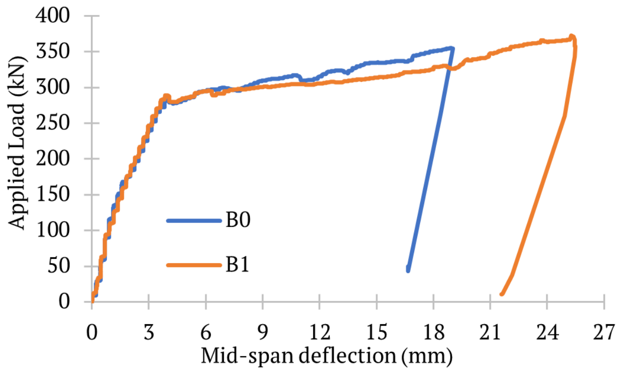
Figure 7. Three-point bending test setup configuration with the locations of the LVDTs (units in mm).

Due to the safety limitations of the loading machine, the test was terminated at a load of 350 kN. From this three-point bending test, several datasets, including the applied load and beam deflection, were obtained and analyzed. The stiffness and ductility of the beam were determined using the collected data. The crack that appeared after the test were observed to determine the failure mechanism of the tested specimen.

3 RESULTS

3.1 Load-Displacement Curve

Figure 8 (a), (b), and (c), as well as Table 2 show the results of the loading test. At first, both B0 and B1 specimens exhibited a relatively comparable initial stiffness in the linear elastic zone. Specimen B0 experienced initial yielding at a load of 283.07 kN, while specimen B1 exhibited initial yielding at 288.91 kN. This represents a 2.44% increase in initial yield load relative to B0. At yield, the mid-span deflection of the specimen B0 and B1 was 4.04 mm and 3.94 mm, respectively. Moreover, the mid-span displacement of the specimen B1 was 2.28% lower than that of specimen B0. Following this, both specimens experienced a marked reduction stiffness. However, the post-yield stiffness of the specimen B0 appears to be slightly higher than specimen B1. The loading test was terminated at 350 kN. At this point, the midspan deflection of specimen B0 reached 17.81 mm, while that of specimen B1 reached 21.40 mm. This indicates that, at the same level of loading, the displacement of B1 was 20.16% lower than that of B0.



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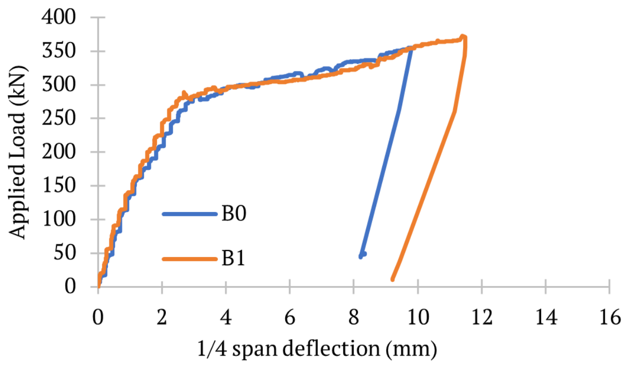

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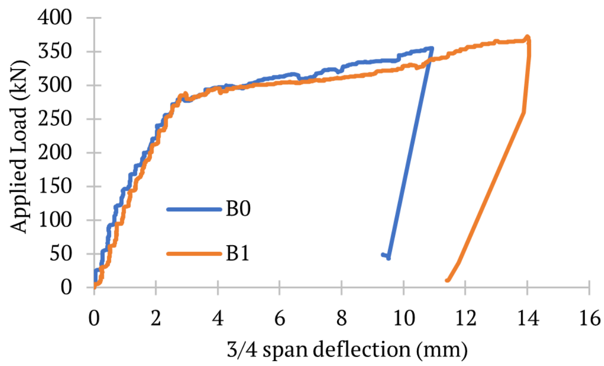


(c)

Figure 8. Load Displacement Curve of The Tested Beams: (a). at mid-span, (b). at ¼ span, (c) at ¾ span.

The load-displacement curve at the quarter-span of the

Table 2. Beam Test Result

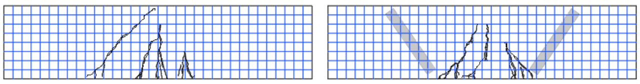
Beams	At yield		At 350 kN
	Load (kN)	Midspan deflection (mm)	Midspan deflection (mm)
B0	283.07	4.04	17.81
B1	288.91	3.94	21.40

beam depicted a similar response to that at the mid-span (see Figure 8 (b) and (c)). The B0 and B1 specimens demonstrated a quite comparable stiffness at early stage of loading phase, and a significant decrease after the applied load increased to 280 kN. At a load of 283.07 kN (yield load of specimen B0), the ¼ span and ¾ span deflection were 3.04 mm and 2.88 mm, respectively. However, for specimen B1, the ¼ span and ¾ span deflection were 2.68 mm and 2.94 mm at a load of 288.91 kN (yield load of specimen B1), respectively. At yield point, the deflection at the ¼ span and ¾ span of specimen B1 was 11.64% and 2.22% lower than those of specimen B0.

3.2 Crack Patterns

Figure 9 and Figure 10 illustrate the cracks developed during the loading test. In Figure 9 (a), at a load of 194 kN, both specimens B0 and B1 experienced several flexural and shear-flexural cracks initiated in the middle of the span. A shear crack was fully formed in B0 specimen, forming approximately 45-degree angle relative to the beam's longitudinal axis. However, at the same load level, only shear-flexural crack was developed on the specimen B1 as presented in Figure 9 (b). The crack propagated in this specimen forming approximately 60-degree angle relative to the beam's longitudinal axis. The cold-formed steel plates were able to prevent early shear crack formation in the beam.

At approximately 278 kN (see Figure 9 (b)), when the shear capacity of the reinforced concrete beams was achieved, there was no significant difference between the crack in the specimen B0 and B1. Both specimens experienced combined shear and flexural cracks. Figure 9 (c) demonstrates the same condition, when the nominal moment of the reinforced concrete beam was achieved after a load of 282 kN was applied at the beam's midspan. The resulting crack pattern was comparable, with additional shear cracks forming adjacent to the initial shear crack on the left side of specimen B0. At the final stage of the loading test, the flexural and shear-flexural cracks of each specimen extended and reached the top surface of the reinforced concrete beam, as presented in Figure 9 (d). Furthermore, at the end of the loading test, there was no separation between the concrete and the cold-formed steel plates.



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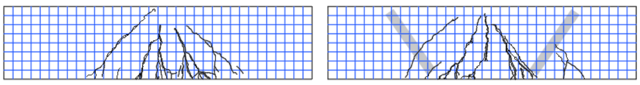

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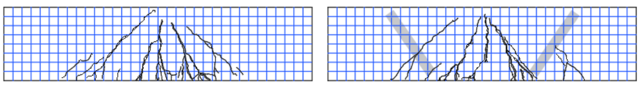

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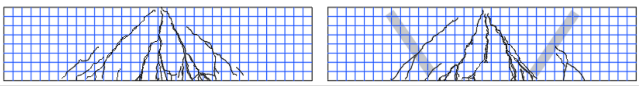
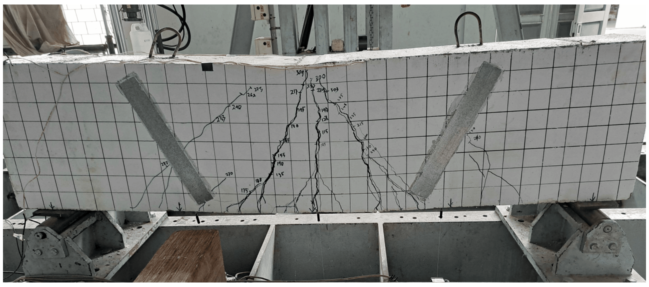


(d)

Figure 9. Crack propagation of the B0 (left) and B1 (right) specimen: a) at a load of 194 kN, b) at a load of 278 kN, c) at a load of 282 kN, and d) at a load of 350 kN.

(a)



(b)

Figure 10. Crack observed after loading test: (a) B0 specimen, and (b) B1 specimen.

4 DISCUSSION

4.1 Strength and Stiffness of the Retrofitted Beam

The capacity of specimen B0 (i.e., specimen without cold-formed steel plates) as well as the corresponding applied load was calculated and tabulated in Table 1. The mid-span deflection of the beam, at several levels of loading was shown in Table 3. When the first crack of B0 reached the top surface of the beam, the mid-span deflection of the B0 and B1 specimens was similar. However, the mid-span deflection of B0 specimen tended to be greater than that of B1 after the shear crack formed. When the shear strength of the reinforced beam was surpassed, the displacement of B0 was 3.84 mm, while the deflection of the B1 reached 3.62 mm. The deflection of B0 was 6.01% higher than that of B1. When the moment capacity of the beam was attained, the midspan deflection of B0 and B1 was 4.04

mm and 3.67 mm, respectively. This means that the mid-span displacement of B0 was 10.18% higher than that of B1. Furthermore, this indicates that the cold-formed steel attached to the reinforced concrete beam contributed to enhancing the stiffness of the beam during the early loading stage. This is further confirmed by the beam stiffness calculations presented in Table 4.

Table 3. Midspan deflection correspond to load at first shear crack, nominal shear capacity, and nominal moment capacity

Condition (load)	Mid-span deflection	
	B0 (mm)	B1 (mm)
First shear crack of B0 reached the beam top surface (194 kN)	2.26	2.26
Beam's nominal shear achieved (278.82 kN)	3.84	3.62
Beam's nominal moment achieved (282.48 kN)	4.04	3.67

As presented in Table 4, the initial stiffness of B0 and B1 was 85.98 kN/mm and 86.00 kN/mm, respectively. However, after the shear crack propagated to the top surface of the beam specimen, the beam stiffness of B0 was reduced to 53.61 kN/mm, approximately 37.64% lower than the initial stiffness. The specimen B1 was also experienced a decrease in stiffness, approximately 27.87% lower than the initial stiffness. The reduction in beam stiffness may be caused by crack propagated in the beam, which diminished the effective cross-sectional area of the reinforced concrete beam. However, the reduction in stiffness appeared to be higher for the specimen without the cold-formed steel strengthening. A significant decline in the beam's stiffness was found once the yield load of the beam was surpassed. The stiffness of the B0 and B1 specimens was 4.86 kN/mm and 3.50 kN/mm, respectively.

Table 4. Stiffness of the specimens tested

Condition	Stiffness (kN/mm)	
	B0 (mm)	B1 (mm)
Initial condition, before 194 kN (load correspond to first shear crack of B0)	85.98	86.00
194 kN until yield load	53.61	62.03
After yield load	4.86	3.50

Specimen B0 exhibited approximately 92% decline in stiffness after the plastic deformation occurred in the specimen. Furthermore, at the same condition, the extreme reduction in stiffness of specimen B1 reached 94%. Reduction in beam stiffness can be influenced by several factors. The cracks that developed on the concrete surface increased in number and propagated further, resulting in the reduction of the effective cross-sectional area. This caused the beam to have lower stiffness. The plastic deformation of the reinforcement bar can also cause the beam to drop. Once the steel reinforcement yields, the plastic stress-strain behavior appeara and affects the beams's response to applied load.

The findings of this research are consistent with those reported by Puluhulawa et al. (2022). In their study, the authors used cold-formed steel as shear strengthening, placed vertically inside concrete beams. During the early phase of the beam loading test, both beam samples – one unstrengthened beam and the other reinforced with cold-formed steel – exhibited comparable stiffness. However, the strengthened beam then showed a greater reduction in stiffness as loading increased and was able to resist higher ultimate load. The stiffness response of the beam retrofitted with cold-formed steel plates differs from those retrofitted with steel plates. Reinforced concrete beams strengthened by steel plates typically exhibit greater stiffness from the early loading stage, this enhanced stiffness tends to persist even beyond the yield point, as the beam transitions into the plastic deformation phase (Hamoda et al., 2024).

4.2 Ductility of the Retrofitted Beam

Ductility in a structure is the ability of the structure to undergo large deformations before failure. A ductile structure means that the structure is able to absorb energy through hysteretic behavior during dynamic loads such as earthquakes or other time-varying loads. Increasing ductility in a structure allows the building to resist seismic loads effectively (Anam, 2016).

Although the loading test was terminated before reaching the ultimate load, specimen B1 appears to exhibit ductile behavior. The load-displacement curve of B1, particularly after beam yielding and significant reduction in stiffness was found, indicates a more ductile response, characterized by increased deformation capacity under slowly progressing loading. At the same load level, specimen B1 exhibited 20.16% greater deflection than B0 (see Table 2). The ductility index could not be determined using the available data since the loading test was stopped at 350 kN, prior to specimen failure. However, from the presented data (using displacement data at a load of 350 kN), the ductility index of the specimen B1 is estimated to be greater than 5.90. Cold-formed steel as a strengthening material provides adequate ductility, especially when compared to other methods presented in Table 5. Ductility plays an important role in the buildings, especially those located in earthquake-prone area. Several factors can influence the ductility of a beam, including reinforcement details, concrete type, as well as the strengthening material used on the beam.

Several previous studies have shown that retrofitting techniques using externally bonded plates can influ-

Table 5. Ductility of Strengthen Reinforced Concrete Beam

Researcher	Specimen detail	Ductility Index
Haryanto et al. (2012)	T-section beam without strengthening	5.77
	T-section beam with wire rope and mortar composite strengthening	2.10 - 3.60
Aykac et al. (2013)	Rectangular section beam without external reinforcement	16.80
	Rectangular section beam, reinforced with externally steel plate	6.50 - 20.90
Hawileh et al. (2014)	Rectangular section beam (control beam)	3.50
	Rectangular section beam, retrofitted with CFRP	2.16
	Rectangular section beam, retrofitted with GFRP	2.80
	Rectangular section beam, retrofitted with GFRP and CFRP	1.59 - 2.02
Shanmugavelu et al. (2015)	Rectangular section beam, retrofitted with GFRP laminates	3.79 - 4.30
Fayyad and Lees (2017)	Lightly reinforced concrete beams, rectangular section	1.80 - 2.37
Renić and Kišiček (2021)	Rectangular concrete beam reinforced with FRP rebar	1.90 – 3.60

ence the ductility of strengthened beams. A study conducted by Rasheed et al. (2017) showed that the ductility of reinforced concrete strengthened with externally bonded aluminum alloy plates decreased. The strengthened beams exhibited lower ductility than unstrengthen ones. Excessive use of such plates may significantly reduce the beam's ductility, therefore the number of plates attached to the beam should be carefully considered to avoid drastic reduction in stiffness.

4.3 Crack Pattern of the Retrofitted Beams

In this study, the beam was subjected to three point bending test, in which a concentrated load was applied at the midspan of the beam. During the loading test, the maximum bending moment occurred at the midspan of the beam, while the shear force remained relatively uniform from the supports to the center span of the beam. This test set up induces tensile stress at the bottom surface of the beam as well as compressive test at the top surface of the beam. This results in cracks, and the crack behavior during the test reveals the failure mechanism of the beam. In reinforced concrete beams, a complex crack pattern can develop in the structure and depends on several factors, including the geometry of the structural element, local defects emerging during the construction, the percentage of reinforcement provided, as well as the bonding between concrete and reinforcings bar inside the beam (Carpinteri et al., 2007).

The crack pattern of the specimens was observed after the loading test and showed that there were subtle differences between the conventional reinforced concrete beam specimen (B0) and the strengthened beam specimen (B1). Both B0 and B1 experienced flexural-shear cracks, as indicated by crack patterns propagating from the bottom of the beam to loading point and forming specific angles. However, the cracks in specimen B1 tended to be stepper, indicating that the bending moment mechanism played a more dominant role in the reinforced concrete beam retrofitted with cold formed-steel plates. The behavior of bending shear – crack was different from shear and compression cracks and may be caused by more complex reinforcement within the beam structure (Huang et al., 2025).

In contrast, the shear strengthening using embedded cold-formed steel plates conducted by Puluhulawa et al. (2022) showed a different behavior. Both the strengthened and unstrengthened beams exhibited shear crack that formed at approximately a 45 – degrees of angle. The difference in the types and mechanism of cracks between this study and previous research may be caused by the difference in the setup of the strengthening elements. In this study, the cold-formed steel plates were placed outside the concrete beams, inclined, and bonded with epoxy. In the previous research, the cold-formed steel plates were attached inside the concrete beam, placed at uniforms spacing along beam, and adhered to the stirrups of the beam.

4.4 Limitation on the Retrofitting Application

The application of cold-formed steel plates as an external shear strengthening method for reinforced concrete (RC) beams has gained considerable attention in recent years, primarily due to its practicality, ease of application, and significant structural benefits. Retrofitting RC structures using externally bonded steel plates is a well-established technique, widely recognized for its simplicity, cost-effectiveness, and its ability to substantially enhance the structural capacity of deficient beams and slabs. Steel plates contribute high stiffness and strength, leading to notable improvements in both flexural and shear performance. This is particularly important for RC beams that were originally underdesigned or have deteriorated due to aging, environmental exposure, or increased load demands (Makhlouf et al., 2024). One of the primary advantages of this method is the significant increase in shear capacity that it provides, which is crucial in preventing brittle shear failures that can be catastrophic in concrete structures.

Research on similar strengthening materials, such as carbon fiber-reinforced polymer (CFRP), has highlighted the influence of the internal reinforcement ratio on debonding behavior. For instance, Thamrin et al. (2021) investigated how the amount of internal steel reinforcement affects the debonding moment in RC beams strengthened with externally bonded CFRP plates. Their study revealed that beams with higher reinforcement ratios exhibited improved flexural performance and delayed debonding failure. However, they also noted that the full strain capacity of the CFRP plates was often not achieved, as premature debonding or other failure mechanisms limited the ultimate performance of the strengthened beam. This insight is critical because it underscores the limitations inherent in external strengthening techniques, including those using steel plates, where the bond between the plate and concrete can be a weak link.

The relatively fast installation process is another key advantage of using cold-formed steel plates. Unlike traditional strengthening methods that may require extensive demolition or significant downtime, this technique can be applied efficiently, especially when modular or prefabricated steel plate systems are used. This makes it highly suitable for urgent repairs and retrofitting of existing structures with minimal disruption. Furthermore, the method is versatile, performing effectively across a range of span-to-depth ratios and structural geometries, which adds to its practicality for various engineering applications.

Despite its advantages, cold-formed steel plate retrofitting presents several challenges and limitations that must be carefully addressed to ensure reliable and long-lasting performance. A primary concern is the risk of premature debonding at the interface between the steel plate and the concrete surface, which often occurs before the steel plate's full strength is mobilized. This premature failure mode is commonly attributed to inadequate bonding quality or insufficient anchorage systems. Proper anchorage is particularly challenging in field conditions or when dealing with irregularly shaped structural elements. Studies by Makhlouf et al. (2024) emphasize that even with appropriate adhesive bonding, the lack of sufficient mechanical anchorage can lead to early debonding. Therefore, implementing mechanical anchorage devices or advanced anchoring methods is essential to enhance bond reliability and ensure long-term performance.

The added weight from the steel plates, which, although relatively minimal compared to other strengthening materials, can still increase the structural demand on existing supports and foundations. This aspect must be evaluated during the design phase to avoid unintended consequences such as overloading secondary elements. Additionally, corrosion poses a significant long-term durability concern for steel plate retrofitting, especially in environments exposed to moisture, chloride ions, or aggressive chemicals. Without proper protective coatings or maintenance strategies, the steel plates can deteriorate over time, compromising the structural integrity of the retrofit.

Moreover, the use of stiff steel plates in retrofitting may inadvertently reduce the ductility of the strengthened member. Over-strengthening certain sections can induce stress concentrations, shifting failure modes to less desirable brittle mechanisms in other regions of the beam. This phenomenon can diminish the overall energy dissipation capacity of the structure and reduce its seismic resilience, which is critical in earthquake-prone areas (Chandrakanth and Kavitha, 2020).

Cold-formed steel plate retrofitting offers a highly promising and practical solution for enhancing the shear capacity and overall performance of RC beams. However, the effectiveness of this technique depends heavily on careful design, detailing, and execution. Addressing challenges such as debonding, anchorage, corrosion, and ductility reduction is vital for achieving safe and durable strengthening. Further research, particularly focusing on behavior under cyclic or real-life loading scenarios, as well as the development of comprehensive design guidelines, is necessary to fully integrate cold-formed steel plate retrofitting into mainstream structural engineering practice.

5 CONCLUSION

This study explores the potential use of cold-formed steel plates as an alternative material for shear strengthening in reinforced concrete beams. A beam with a cross-sectional dimension of 400 × 250 mm and a clear span of 1500 mm was evaluated using a three-point bending test. Two specimens were tested: B0, a conventional concrete beam without strengthening, and B1, a beam externally strengthened with cold-formed steel plates. The plates were installed at a 45-degree angle relative to the beam's longitudinal axis and bonded using epoxy adhesive at both sides of the concrete beam web. Due to safety considerations and the limitations of the testing equipment, the loading was terminated at 350 kN.

The results indicate that shear strengthening with cold-formed steel plates can increase the beam stiffness in the early loading stages. Cold-formed steel plates can prevent early shear cracks in the beam. Both specimens exhibited plastic deformation after the applied load increased to 280 kN. Although the test was stopped before reaching the ultimate load, specimen

B1 exhibited more ductile behavior compared to B0. At the yield load, the deformation of the specimen B1 was 2.28% higher than that of specimen B0. Furthermore, the mid – span deflection of specimen B1 was 20.16% larger than specimen B1 at a load of 350 kN.

The decrease in beam stiffness was clearly visible after the shear capacity of the beam was surpassed. Additionally, the crack pattern in the strengthened beam was primarily governed by bending moment mechanisms, as evidenced by the steeper crack angles observed during testing.

DISCLAIMER

The authors declare no conflict of interest.

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