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Experimental Study on Flexural Performance of lap-spliced and mechanical-spliced (clamp type) rebars in RC Beams

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Abstract

Various methods can be employed to splice reinforcement bars, including lap splicing, welding, and mechanical splicing. Lap splicing is the most used method among these techniques. However, this study primarily focuses on evaluating the potential of mechanical splicing to replace the lap splice method. The investigation involved assessing the flexural performance of six RC beams in a series of laboratory experiments. These beams represented a control beam, an RC beam with lap-spliced rebars, and an RC beam with clamp-type mechanical-spliced rebars. The laboratory testing results indicated that the RC beam with lap-spliced rebars had the highest load-bearing capacity, resulting in the highest nominal flexural moment (Mn). In contrast, the control beam demonstrated the highest deflection, signifying a greater level of ductility. However, RC beams with mechanical splices (clamp type), while not achieving the highest flexural moment and ductilities, are still competitive, as the experiment revealed that the difference is not significant. Consequently, it can be concluded that mechanical splicing has the potential to compete with or replace lap splicing in RC beams.

Keywords

Lap splice, Mechanical splice, Clamp connector, Flexural moment, Flexural crack, RC beam, Ductility

1. Introduction

Around the world, reinforced concrete is frequently used in a variety of constructions. A reinforced concrete element can be produced by combining reinforcing bars with sufficient tensile strength and concrete with adequate compressive strength. Reinforced concrete (RC) components such as columns, beams, slabs, and shear walls are frequently used in multi-story buildings. For reinforced concrete, load calculations are important throughout the design stage to guarantee that the highest levels of safety and economic requirements are met (Mahlisani & Teguh, 2014).

For the load to be transferred from the slabs to the columns, RC beams are essential. This load causes the columns to bend and experience axial compression, which transfers force to the foundation. The strength of a flexible beam structure like the one just described is affected by things like the concrete's compressive strength, the reinforcement's yield stress, the length of the beam, and the stiffness of the beam. Consideration should also be given to ductility. Buildings must be built with high ductility, or the ability to withstand significant deformations without breaking suddenly under applied loads (Shin et al., 2010). Because RC beams are frequently characterized as tension-controlled elements, they are created under a scenario of insufficient reinforcement, where failure occurs first (Teguh & Mahlisani, 2016).

The size and length of RC beam rebars used for construction might vary. However, manufacturing and shipping factors frequently place a limit on the length of the rebar (Mabrouk & Mounir, 2018; Tarabia et al., 2016). Hence, rebar splicing is consequently required. Rebar splicing is essential to the behavior of reinforced concrete elements and structures by transferring stress from one bar to another (Dabiri et al., 2022). Rebar can be joined using various techniques, such as lap, mechanical, and welded splicing (Musyaffa & Jafar, 2022; Sulastri, 2020). The lap splice technique is the most frequently used in buildings. The standard method of lap splicing entails placing an adequate length of rebar at the spliced location (Dahal & Tazarv, 2020). Both a contacted and a non-contacted splice can be carried out. Lap splices do have certain negatives, though, such as reinforcing congestion in the spliced area, greater rebar weight overall that has an adverse impact on both the environment and the economy, and a decrease in strength or displacement capacity in places that are susceptible to inelastic deformation (Kheyroddin & Dabiri, 2020; Tarquini et al., 2019). Mechanical splices are a substitute for lap splicing. In previous studies, the use of clamp type mechanical splice has been discussed, but only limited to tensile and compressive strength tests such as research conducted by Tavio and Parmo (Parmo & Tavio, 2015; Tavio & Parmo, 2016). The mechanical splices according to ACI 439.3R-91 are divided into three classifications: Compression only Mechanical Splice, Tension only Mechanical Splice, and Tension-Compression Mechanical Splice. The shortcomings of lap splices may be addressed using mechanical splices. This study investigates the potential for mechanical splicing to take the role of the lap splice technique.

The goal of this study is to determine whether mechanical splices in RC beams can provide better performance and behavior than the widely utilized lap splices in construction. Rarely do researchers evaluate the performance and behavior of RC beams with mechanical splices. So, the purpose of this study is to answer that query. On RC beam specimens with various splice types, such as lap splices and clamp-type mechanical splices, a series of experimental experiments were carried out. The outcomes were contrasted with those of a control beam specimen (RC beam with no rebar splice). The aim is to understand how reinforced beams with and without rebar splices perform in comparison. Flexural strength, ductility, and the formation of crack patterns (collapse) are among the performance characteristics that were found.

1.1 Lap Splice

The lap splice is a commonly used construction technique known for its efficiency and simplicity (Alyousef et al., 2018). It can be divided into two main types: "contacted" and "non-contacted." In a contacted lap splice, the spliced reinforcing bars are positioned next to each other and connected using wire (as depicted in Fig. 1a). The minimum spacing between adjacent contact lap splices should adhere to the larger of the following criteria: 1 inch, the diameter of the bar (db), or 4/3 times the diameter of the aggregate (dagg).

In contrast, a non-contact lap splice involves placing the reinforcing bars parallel to each other but leaving gaps or spaces between them (as shown in Fig. 1b). The maximum transverse center-to-center spacing between these spliced bars should not exceed the smaller of the following criteria: 1/5 of the required lapped length or 6 inches (American Concrete Institute, 2014; Badan Standardisasi Nasional, 2019).

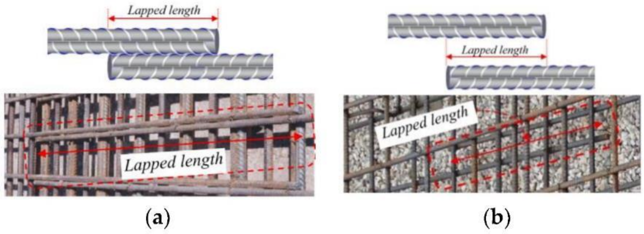


Fig. 1 Lap splice (a) contact (b) non-contact (Fayed et al., 2023)

Various factors impact the effectiveness of lap splices, encompassing concrete cover, the length over which bars are lapped, the ratio of the applied rebars, rebar diameter, presence of transverse reinforcements in the spliced area, concrete properties, and the positioning during concrete pouring (Mabrouk & Mounir, 2018) (Al-Quraishi et al., 2019; Goksu et al., 2014). Nevertheless, in compliance with ACI 318-14 and SNI 2847:2019, lap splicing is restricted to rebars with a diameter of less than 36 mm. This limitation arises from the absence of ample experimental data concerning lap splicing for larger diameter rebars.

1.2 Mechanical Splice

According to ACI 439.3R-91 (ACI 439.3R-91, 1999), mechanical connections are grouped into three main categories: 1) Compression-Only Mechanical Connections; 2) Tension-Only Mechanical Connections; and 3) Tension-Compression Mechanical Connections. Compression-Only Mechanical Connections enable the transfer of compressive stress from one end to another through reinforcing bars aligned in a single axis (concentrically). Tension-Only Mechanical Connections are utilized in scenarios where the reinforcement experiences solely tensile stresses, such as in cases of flexural reinforcement or expansion shrinkage reinforcement. Within the category of Tension-Only Mechanical Connections, we can find examples like the Steel Coupling Sleeve with Wedge and the Double Barrel Bar Splice. This type of connection has the capability to withstand loads up to 125% of the yield stress of the connected reinforcing steel. It can also be employed to join reinforcing steel of varying diameters (Tavio & Parmo, 2016). Tension-Compression Mechanical Connections fulfill a dual function by accommodating both tension and compression forces. This category includes connection types like the Cold-swaged Coupling Steel Sleeve and the Taper-Threaded Steel Coupler. Several examples of mechanical connection can be seen in the Figures below.

(a) Wedge-Locking Coupling Sleeve

(b) Bar Splice Double Barrel

(c) Cold-Swaged Steel Coupling Sleeve

(d) Solid-type steel coupling sleeve

Fig. 2 Several types of mechanical splices (ACI 439.3R-91, 1999; Tavio & Parmo, 2016)

2. Materials and Method

In this research, a laboratory-based experimental approach is utilized. A set of well-structured laboratory experiments is carried out on prepared samples to gauge a range of factors, including maximum load capacity, maximum deflection, yield strength, tensile strength, compressive strength, and the pattern of cracks. These tests were conducted at the Engineering Mechanics and Structures Laboratory and the Engineering Construction Materials Laboratory, both located within the Department of Civil Engineering, Faculty of Civil Engineering and Planning, Islamic University of Indonesia in Yogyakarta.

2.1 Test Specimens

The specimens utilized in this study consisted of reinforced concrete beams with dimensions of 200 x 300 x 2000 mm (width x depth x length). For each experimental variant, two test specimens were prepared, and there was a total of three variants, resulting in six reinforced concrete beam specimens in total. Each variant was distinguished by the type of splicing used: an RC beam without splicing (serving as the control specimen), an RC beam with lap splice rebars, and an RC beam with clamp connector type mechanical splice.

The properties of the RC beams were as follows: a concrete compressive strength (f'c) of 25 MPa, a rebar yield strength (fy) of 420 MPa for deformed bars, and 280 MPa for plain rebars. Deformed rebars with a diameter of 13 mm (D13) were employed as tension bars, while plain rebars were used for compression bars (Ø10) and stirrups (Ø8). For more detailed information, the variations of the test objects can be observed in Fig. 5, Fig. 6, and Fig. 7. Further specifics regarding the reinforcement of the RC beam specimens can be found in Table 1.

Additionally, concrete cylinder tests were conducted as part of this research series. For every RC beam specimen, a concrete cylinder was supplied to measure the concrete's actual compressive strength (f'c). Similarly, for the reinforcing bars, tensile strength tests were performed to determine the actual yield and tensile strength (fy) of the rebars. These values, f'c and fy, play a crucial role in estimating the nominal moment (Mn) provided by the RC beams using analytical formulas.

The lapped length was calculated using equation written in SNI 2847-2019 and the specified criteria, resulting in a calculated lap splice length of 346.667 mm. This calculation was made under the following conditions: (i) the RC beam is made of normal (non-lightweight) concrete with an estimated f'c value of 25 MPa; (ii) the reinforcing bars were not coated with epoxy; (iii) the diameter of the bars being spliced was 13 mm; and (iv) the estimated fy value of the reinforcement was 280 MPa. This calculated value was then rounded up and adjusted for field installation purposes, leading to a lapped length of 430 mm.

Subsequently, the author realized that the required lap joint length should have been 520 mm, as indicated by the actual tensile test results of the reinforcing steel, which showed an fy value of 464.646 MPa. This value categorizes the reinforcing bars as TS420, whereas the initial assumption was based on TS280. Unfortunately, this realization occurred after all the concrete specimens had been assembled and cast. Consequently, the author decided to continue the research while acknowledging this issue as a limitation in the study.

Table 1. RC beams rebars configuration

Specimens	Rebar Placement			Splicing Type
	Longitudinal Bars		Stirrups	
CB-1	Top Bottom	2P10 2D13	P8-150	No Splicing (Control Beam)
CB-2	Top Bottom	2P10 2D13	P8-150	
LSC-1	Top Bottom	2P10 2D13	P8-150	Contacted Lap Splice
LSC-2	Top Bottom	2P10 2D13	P8-150	
MSC-1	Top Bottom	2P10 2D13	P8-150	Mechanical Splice Clamped Type
MSC-2	Top Bottom	2P10 2D13	P8-150	

Note:
D = Deformed rebar
P = Plain rebar

In this research, the clamp connector (mechanical splice) design is based on the research conducted by Ginting (2014). The clamp is created using 5 mm thick steel plate material, which is pressed to achieve the desired shape. Fig. 3 and Fig. 4 below is the clamp design employed in this study. Detailed information is as follows: db = 8 mm, S1 = 15 mm, S2 = 20 mm, L = 30 mm, b = 26 mm, t = 3 mm, Sp = 20 mm, and tp = 5 mm. See Fig. 3 below.

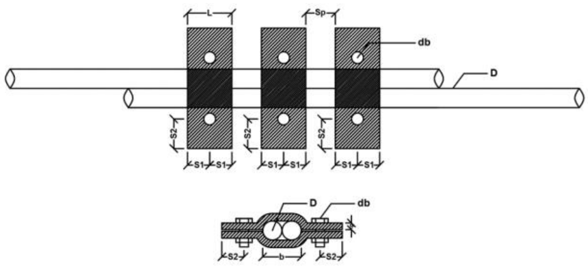


Fig. 3 Design of clamp connector

Fig. 4 Clamp connector used in this research

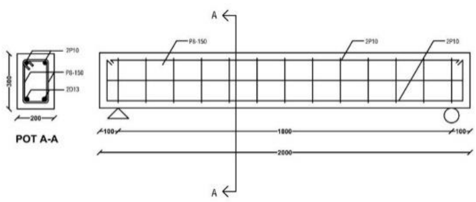


Fig. 5 Detail reinforcement of RC beam without rebar splicing (CB)

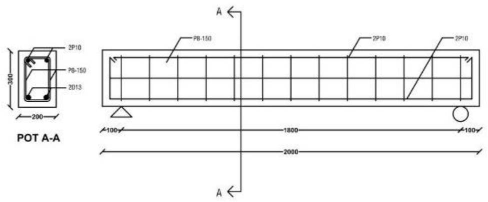


Fig. 6 Detail reinforcement of RC beam with lap splice (LS)

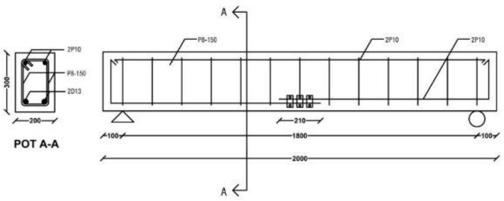


Fig. 7 Detail reinforcement of RC beam with mechanical splice (MSC)

2.2 Experiment Setup

The RC beam specimens were conceptualized as simply supported beams with a clear span of 1800 mm, placed on pin and roller supports at each end. The laboratory experiment employed a 2-point loading configuration, with the loads applied 600 mm apart. A hydraulic pump was used to gradually increase the load until the ultimate load was reached, causing the beam to fail. Additionally, Linear Variable Differential Transformers (LVDT) were installed at three points between the two loads to monitor the deflection that occurred during the testing process. All the data was recorded using a data logger. You can find illustrations of the test setup and the actual test setup for RC beam specimens in Fig. 8 and Fig. 9. In this study, an additive was introduced to expedite the hardening process, enabling the tests to be conducted at 14 days of concrete age.

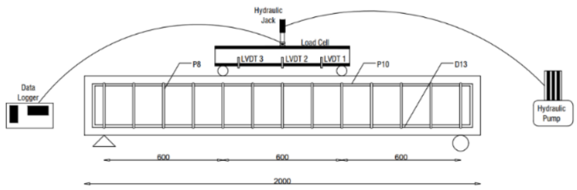


Fig. 8 The illustration of experiment setup

Fig. 9 Experiment setup

3. Results and Discussion

3.1 Rebar Tensile Strength and Concrete Compression Strength Test

Tensile testing of rebars was performed to ascertain the yield and tensile strength values of rebars used in RC beams. The test results revealed that the yield strength (fy) and tensile strength (fu) of the rebars without splicing were 464.647 MPa and 646.633 MPa, respectively.

For each RC beam specimen, a concrete cylinder was provided and examined to determine the compressive strength (f'c) of the concrete. These concrete cylinders were subjected to compression testing using a testing machine once they reached 14 days of age. Typically, concrete specimens are tested at 28 days of age. However, in this study, a specific additive was incorporated into the mixing process to expedite the concrete's hardening. As a result, both the RC beams and the concrete cylinders were tested on the 14th day.

The test results of the concrete cylinders are detailed in Table 2. Based on the report, it can be concluded that all the concrete compressive strength values (f'c) have met or exceeded the minimum desired value of 25 MPa. This suggests that the proportions of cement, coarse and fine aggregates, and water used in the concrete mix design were accurate.

Table 2. Properties of concrete cylinders

Specimens	Diameter (mm)	Height (mm)	Section Area (mm^2)	Recorded Ultimate Load (kN)	f'c (Mpa)
C-CB-1	150.8	299.6	17860.457	595	33.314
C-CB-2	150.8	299.6	17860.457	540	30.234
C-LSC-1	149.3	289.3	17506.910	455	25.990
C-LSC-2	149.7	299.4	17600.844	555	31.533
C-MSC-1	149.1	302.3	17460.037	570	32.669
C-MSC-2	149.7	299.4	17600.843	625	30.845

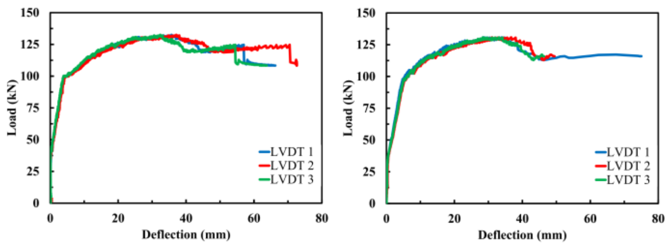
3.2 The Flexural Strength Test on RC Beams

The flexural strength test was carried out on reinforced concrete beam specimens to investigate their behavior under bending, including aspects such as bending moment capacity, deflection, and crack patterns. The results obtained from the flexural strength test of these reinforced concrete beams include the maximum load measured in kN units and the deflection measured in mm units, which were recorded using the LVDT. Additionally, the test allowed observation of the crack patterns that developed during the application of load using the hydraulic jack.

The maximum load and deflection values can be found in Table 3. Graphs depicting the relationship between load and deflection can be observed in Fig. 10, Fig. 11, and Fig. 12.

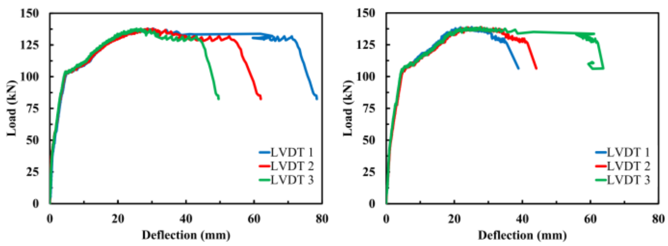
Table 3. Maximum loads and deflections

Specimens	Max. Load (kN)	Max. Deflection (mm)		
		LVDT 1	LVDT 2	LVDT 3
CB-1	132.55	66.284	72.600	63.760
CB-2	130.788	100.747	75.575	65.019
LS-1	137.844	78.445	61.977	49.576
LS-2	138.852	38.844	44.076	63.764
MSC-1	134.82	69.676	85.592	72.976
MSC-2	126.504	79.223	69.26	54.897



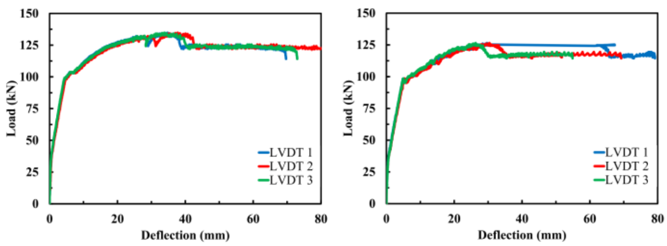
(a) CB-1 (b) CB-2

Fig. 10 Load VS Deflection Graphs for CB



(a) LS-1 (b) LS-2

Fig. 11 Load VS Deflection Graphs for LS



(a) MSC-1 (b) MSC-2

Fig. 12 Load VS Deflection Graphs for MSC

According to Table 3, the control beam has a maximum average load of 131.67 kN. Beams with lap-spliced rebars and clamped rebars exhibit maximum loads 5.07% higher and 0.97% lower than the control beam, respectively. These findings suggest that both lap splices and mechanical splices demonstrate a load capacity that is at least equal to, if not greater than, the control beam.

This study also observed the ductility of the RC beams. Ductility denotes the capacity of structural components to experience substantial deformation without experiencing abrupt failure (Shin et al., 2010). Ductility is of vital importance in averting structural failure because a ductile structure offers early warning indicators before any failure takes place (Mahalingam et al., 2013). Ductility can be categorized based on deflections (deflection ductility), strains (strain ductility), and curvature (curvature ductility) (Irheem et al., 2018). Deflection ductility relies on the overall configuration of the structural member and its load application. It is quantified as the ratio of deflection at the point of ultimate load to the deflection at the yield load, as represented by the load-deflection diagram. In contrast, strain ductility is influenced by the material properties and is described as the ratio of strain at ultimate load to the strain at yield load, as depicted in the stress-strain diagram. Curvature ductility, on the other hand, is related to the shape and size of the cross-section of the reinforced concrete member. It can be defined as the ratio of curvature at ultimate load to curvature at yield load. Based on the given definitions, in this study, deflection ductility is chosen to describe the ductility of the RC beams. The result is displayed in Table 4.

Table 4. Displacement ductility

Specimens	Deflection (mm)		Ductility
	Δu	Δy	(μ_Δ)
CB-1	32.4	4.4	7.36
CB-2	31.058	5.398	5.75
LS-1	28.617	5.062	5.65
LS-2	27.902	5.041	5.54
MSC-1	37.746	5.299	7.12
MSC-2	30.383	5.299	5.73

According to Table 4, the lowest ductility observed in the control beam is 5.75. This value serves as a benchmark for the other RC beams. As shown in the table, both the RC beams with lap splicing and the RC beams with mechanical splicing exhibit similar levels of ductility. Therefore, it can be concluded that lap splice rebars and clamped rebar connections can, at the very least, match the ductility of non-spliced rebars.

3.3 The Flexural Moment of RC Beams

Following the completion of laboratory testing and the determination of maximum loads, the actual flexural moment was calculated. This flexural moment, derived from the laboratory tests, was then compared with the flexural moment computed using the analytical (theoretical) formula.

The testing of reinforced concrete beams adhered to the setup described in the research methodology. The concrete beams were supported at both ends in a simple support configuration, and a two-point load was applied at the middle span of the beam. In this setup, it was anticipated that the maximum moment would occur precisely at the midpoint of the beam span. Consequently, the calculated flexural moment represents the bending moment at the mid-span of the beam.

Based on the calculation results, the nominal bending moment values for all specimens are presented in Table 5. Among the laboratory test results, it was observed that the reinforced concrete beams with lap spliced rebars exhibited the highest nominal flexural moment, while those with clamp connections displayed the lowest nominal flexural moment.

Theoretical flexural moment is determined by utilizing various material properties data, including the dimensions of the beam cross-section, the type of reinforcement, the compressive strength of the concrete (f'c), and the yield strength of the rebar (fy). Initially, the beam cross-section size was established as 200x300 mm. For tension reinforcement, 2D13 steel bars were employed, while 2P10 steel bars were used for compression reinforcement, with P8 reinforcement stirrups placed at 150 mm intervals. The result of concrete compressive strength and tensile strength were determined through testing. Theoretical nominal flexural moment values for all specimens were then computed based on these calculations, as presented in Table 5.

Table 5. Experimental and theoretical nominal flexural moment

Specimens	Experimental, Mnx (kNm)	Theoretical, Mn (kNm)	Ratio
CB-1	38.729	37.859	1.023
CB-2	38.200	36.500	1.047
LS-1	40.316	34.133	1.181
LS-2	40.619	37.091	1.095
MSC-1	39.409	33.731	1.168
MSC-2	36.914	32.941	1.121

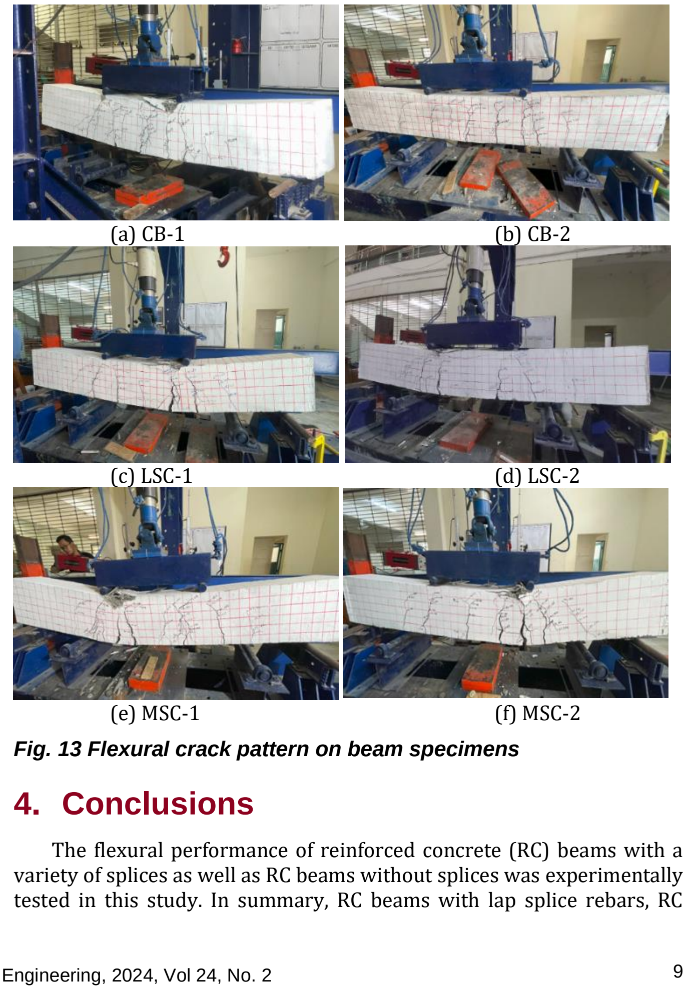
Table 5 indicates that the experimental flexural moment (Mnx) values exceed the theoretical Mn values. This discrepancy can be attributed to certain simplifications made in the theoretical calculations of Mn. Furthermore, the theoretical calculations assume an idealized behavior of the reinforced concrete beam, such as assuming a linear distribution of strain in the concrete based on Bernoulli's principle and assuming no slip between the concrete and the reinforcing steel. In practice, these assumptions may not hold true, and there may be additional complexities and non-linearities in the actual behavior of the beam. These deviations from the theoretical assumptions can result in variations between the estimated and experimental flexural moments. In summary, the experimental flexural moment is influenced by the real-world behavior of the beam and the actual material properties, which can lead to differences compared to the theoretical flexural moment obtained through simplified calculations.

As shown in Table 5, the average Mnx of the lap-spliced beam is the highest at 40.47 kNm. The control beam's Mnx is 4.95% lower, and the Mnx of the RC beam with clamped rebar is 5.7% lower than the lap-spliced beam. The initial hypothesis was that adding normal force through the clamp system would increase friction between the reinforcements, allowing for a reduced overlap length. However, experimental results revealed that the reduction was excessive. The clamp's normal force was insufficient to compensate, resulting in a connection no stronger than the lap splice connection.

3.4 Flexural Crack Pattern

The maximum flexural moments occurred at the mid-span of the beam specimens, leading to the formation of cracks. As depicted in Fig. 13, these flexural cracks tended to propagate along the beam until reaching the yield point. Since the tension was concentrated at the bottom of the RC beam section, the cracks extended vertically from the bottom to the top of the beam. The rebar steels played a crucial role in providing tensile strength to prevent abrupt collapse, as concrete primarily offers compression strength.

The pictures also reveal that multiple cracks developed before reaching the maximum loads. Ultimately, a single significant crack at the point where the curvature was most pronounced was responsible for the structural response failure. Notably, as shown in Fig. 13, no shear cracks were observed, indicating that the beams failed due to flexural moment. Regarding the location of this pivotal single crack causing failure in the RC beams, it was typically situated in the mid-region of the RC beam for CB (control beams). In contrast, for LS (lap splice) beams and MS (mechanical splice) beams, the cracks were slightly offset to the left or right of the RC beam, and only a few minor cracks were observed at the mid-span. This difference might be attributed to the increased cross-sectional area of rebars in the lapped region, as two bars were overlapped in this region. Consequently, major cracks tended to occur outside this lapped region.



(a) CB-1 (b) CB-2
(c) LSC-1 (d) LSC-2
(e) MSC-1 (f) MSC-2

Fig. 13 Flexural crack pattern on beam specimens

4. Conclusions

The flexural performance of reinforced concrete (RC) beams with a variety of splices as well as RC beams without splices was experimentally tested in this study. In summary, RC beams with lap splice rebars, RC beams with mechanical splice rebars, and RC beams without rebar splicing demonstrate a similar flexural performance (nominal flexural moment and ductility). Hence, from this result, it can be concluded that mechanical splice can compete or potentially replace lap splice. Additional concluding remarks regarding the experiment can be summarized as follows:

1. RC beams with lap splicing generally exhibit the highest nominal flexural moment (Mnx) compared to the other specimens (40.47 kNm). The Mnx of control beam is 4.95% lower than and the Mnx of RC beam with clamp connection is 5.7% lower than RC beams with lap splice connection.
2. RC beams without splicing achieved the highest ductility level compared to the other RC beam specimens. Nonetheless, the ductilities of the other RC beams are competitive.
3. The cracks observed in all specimens are primarily flexural cracks.
4. RC beams with lap splice and RC beams with mechanical splice specimens exhibit a similar failure pattern, which occurs slightly offset to the left or right, while the failure of the RC beam without splices takes place at mid-span.

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