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Data-Driven Approach for Selecting Mechanical Rebar Couplers Based on the Shape and Structural Characteristics of Reinforcing Bars for Sustainable Built Environment

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Abstract: In reinforced concrete (RC) structures, splicing is required owing to the length limitations of rebars, insufficient lengths, and transportation issues. In particular, splices connect the rebar of RC structures such as walls, columns, beams, slabs, and joints. Lap splices are the most commonly used method worldwide because they do not require specific equipment or skilled workers. However, lap splices incur high construction costs because of the long splice lengths required for large-diameter rebars in megastructures, as well as issues pertaining to material supply, labor costs, constructability, and project duration. Additionally, approximately 15% more rebar is required because of the overlap. Energy saving for a sustainable built environment is possible if the disadvantage of lap splices, which generate high CO_2 emissions due to the excessive use of rebar, are resolved. Hence, mechanical rebar couplers (MRCs) have been developed. However, despite their advantages, they have not been widely applied in construction sites owing to concerns regarding safety, quality, and constructability. Although various MRCs have been developed, most studies focus only on their structural performance. Therefore, a data-driven approach for selecting MRCs based on the reinforcing bar shape and structural characteristics is proposed in this study. Using a data-driven MRC selection algorithm, using the T-threaded coupler for one rebar over two floors resulted in 56% more efficient labor productivity, 15% shorter assembly time, 17% lower costs, and 26% lower CO_2 emission. Using a developed algorithm, the appropriate MRC can easily and rapidly be selected for frequent design changes.

Keywords: data-driven approach; algorithm; mechanical rebar coupler; comparative analysis; constructability

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1. Introduction

In reinforced concrete (RC) structures, splicing is required owing to bar length limitations in accommodating building heights [1], insufficient lengths from factory production [2–4], and transportation issues [5–8]. In particular, splices connect the rebar of RC structures such as walls, columns, beams, slabs, and joints. Rebar splicing methods used in construction sites include lap splices, gas pressure welding, welded splices, and mechanical rebar couplers (MRCs) [5]. Gas pressure welding and welded splices are not applied owing to disadvantages such as the necessity for skilled workers and difficulties in ensuring quality.

Lap splices are the most common rebar splicing method used worldwide as they do not require any specific equipment or skilled workers [9–11]. Lap splices can incur high construction costs owing to the overlap length required for large-diameter rebars in megastructures such as high-rise buildings, as they can increase both the material supply and labor costs. The increase in dead load due to the rebar in the lap splice area (up to 20% of the total rebar weight) can adversely affect the

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overall behavior of the structure [5]. Moreover, complex rebar splicing and numerous joints render it difficult to organize joints on site and can result in unsatisfactory constructability owing to the improper placement of concrete between the rebars. Additionally, approximately 15% more rebar is required because of the overlap [2,12].

Globally, climate change has led to future droughts, heat waves, and sea level rise. One of the biggest causes of climate change is CO_2 [13], and as the issue of CO_2 pollution has recently become more prominent, international regulations on greenhouse gas emissions are being strengthened [14]. The World Bank Group published the world GDP growth rate [15], and the Construction Association of Korea reported the rebar price of 900 USD/ton. And the unit of carbon emissions of a reinforcement bar of 3.505-ton-CO_2/ton [16], a carbon emission forecast was generated, as summarized in Table 1. Rebar usage increases every year, which is estimated to be about 1.269 billion tons in 2025. And this means that the generation of about 368.9 million tons of CO_2 in 2025 is estimated. In other words, energy saving for a sustainable built environment is possible if the disadvantage of lap splices, which generate high CO_2 emissions due to the excessive use of rebar, are resolved.

Table 1. Forecast of global annual rebar consumption and CO2 emissions.

Year	World GDP growth rate (%)	Rebar (billion ton)	CO_2 emission (Ton·CO_2)
2020	-3.1	1.078	313,481,532
2021	6.0	1.143	332,290,424
2022	3.1	1.178	342,591,428
2023	2.1	1.203	349,785,848
2024	2.4	1.232	358,180,707
2025	3.0	1.269	368,926,128

Compared to other joint methods, MRC can reduce the amount of rebar and reduce CO_2 emissions. Site applications of MRCs are increasing owing to their advantages, as follows: (1) MRCs offer a strong bonding force, thus facilitating the maintenance of structural safety even during disasters such as earthquakes. (2) MRCs can be applied to existing structures, thus rendering them useful for reinforcement and repair work. (3) MRCs shorten the construction period owing to their simplicity. (4) MRCs are a relatively economical method for reinforcing and repairing structures and can thus reduce the overall construction cost [17,18]. (5) MRCs facilitate concrete pouring and compaction [2]. (6) MRCs can reduce the amount of rebar used compared with other splicing methods, thus reducing CO_2 emissions. Hence, MRCs are widely used to strengthen and reinforce buildings.

Despite the abovementioned advantages, MRCs have not been widely applied outside of a few developed countries. This is because the variety and characteristics of MRCs vary significantly worldwide, thus rendering their selection difficult for construction projects. Owing to the increasing demand for modular construction and sustainable construction, which are aimed at reducing CO_2 emissions, MRCs must be investigated more intensively.

In regard to investigations pertaining to MRCs, Hong et al. (2020) tested six groups to identify defects in rebar connections between half grouting sleeves, which included groups featuring insufficient grout height, insufficient compaction, rebar offset, insufficient rebar anchor length, and excessive grouting time, as well as a control group [19]. Han et al. (2018) proposed epoxy mortar-filled threaded couplers and conducted experiments to analyze the seismic behavior of precast columns [20]. Dabiri et al. (2022b) developed and validated a machine learning-based model to estimate the extreme strain of MRCs [21]. In addition, numerous structural experiments on MRCs have been conducted [22–26], and Dabiri et al. (2022a) published a review pertaining to splice methods used for reinforcement steel bars [5]. In general, most studies have focused on rebar splicing methods and experimental approaches. Thus, studies pertaining to MRCs are primarily based on structural experiments.

No study has been conducted that classifies and analyzes MRCs based on the rebar shape and structural characteristics such as deformed and threaded bars. Consequently, organized data

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pertaining to MRCs are not available, thus rendering it difficult to select the appropriate coupler during the construction phase. Therefore, a process for selecting the appropriate coupler based on structural characteristics, i.e., by analyzing and classifying the construction methods while considering the rebar shape of MRCs, must be established. In this regard, a data-driven approach for selecting MRCs based on the reinforcing bar shape and structural characteristics is proposed in this study.

The sequence of this study is as follows:

(1) Existing studies pertaining to MRCs are reviewed.
(2) The characteristics of different types of MRCs are compared.
(3) The performance of different types of MRCs is compared in terms of quality, safety, time, cost, and CO_2 emissions.
(4) A data-driven algorithm model is proposed for selecting the appropriate MRC based on the structural characteristics.
(5) A T-threaded coupler derived using the algorithm model is compared with lap splices in terms of labor productivity, time, cost, and CO_2 emissions.

2. Existing Studies

Various MRCs have been developed worldwide, and their structural performance has been investigated experimentally. For example, researchers have investigated shear screw [27–30], headed bar [31,32], grouted sleeve [33–42], threaded [43], and swaged couplers [43,44].

Additionally, researchers have compared the performance of MRCs based on various standards [21]. Bompa and Elghazouli (2018) discussed the effects of coupler size and type on the ductility and deformation of joined rebars [45], and Bompa and Elghazouli (2019) investigated the inelastic cyclic performance of RC members featuring mechanical reinforcement joints [46]. Dahal and Tazarv (2020) evaluated the behaviors of various types of mechanical bar splices suitable for ductile members, and Haber et al. (2014) developed new bridge columns using mechanical reinforcement joints to connect precast columns to on-site poured foundations [47]. Kheyroddin et al. (2020) investigated the cyclic performance of RC columns with mechanical joints [22], and Rowell et al. (2009) evaluated the performance of mechanical couplers at high deformation rates [23]. Kheyroddin and Dabiri (2020) investigated the performance of RC beam–column joints using couplers [25], and Lloyd (2001) analyzed the performance of reinforcing bars joined by bar lock (shear screw) couplers [27]. However, the abovementioned researchers compared MRCs developed under certain conditions and derived results based on experiments.

Meanwhile, some researchers have categorized and tested MRCs based on their type. Tazarv and Saiidi (2016) classified tension–compression mechanical rebar joints into five common types based on their fixing mechanisms [24]. Dahal and Tazarv (2020) classified them into six types of couplers, i.e., threaded, headed bar, swaged, grouted sleeve, shear screw, and hybrid (a combination of two types) couplers [1]. In these studies, only structural experimental studies were conducted based on the structural mechanisms of MRCs, whereas the reinforcing bar shape and structural characteristics were not considered.

3. Classification of MRCs Based on Rebar Shape

Considering the characteristics of different construction sites, rebars can be classified into deformed bars, threaded bars, and special couplers, whereas MRCs can be classified into three types, as shown in Figure 1. In this study, MRCs applicable to general rebar joint areas such as columns, beams, and slabs are classified into deformed and threaded bars, whereas those applied to areas such as anchors and concrete embedding are classified as special couplers. Among the various couplers, swaged couplers are excluded due to quality issues arising from rebar stretching during joint fastening, and threaded couplers are excluded due to increased costs and longer construction periods, as well as difficulties in applying rebars of different standards. End-processed rebars are excluded due to structural stability defects caused by changes in the rebar structure caused by processing, and

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shear screws are excluded due to quality variances emanating from the manufacturing process and concerns regarding rebar damage during construction.

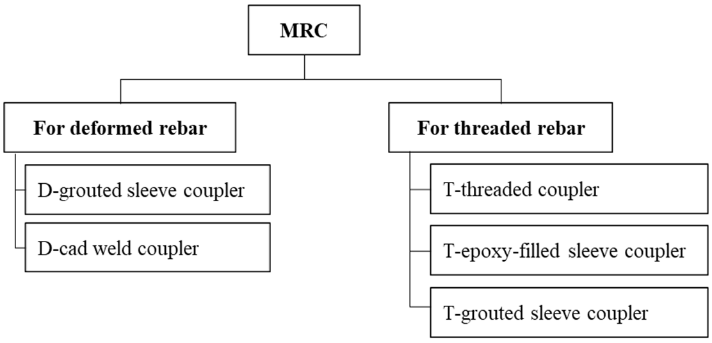

Figure 1. Classification of MRCs.

Joints applicable to deformed bars are classified into two types: D-grouted sleeve couplers and D-cad weld couplers. As shown in Figure 2a, grouted sleeve couplers involve filling mortar between the steel pipe and deformed rebar, thus allowing the stress at the rebar joint to be transferred through the mortar to the steel pipe. D-grouted sleeve couplers comprise three main components: the sleeve, grout, and two holes (grout inlet and grout outlet) [5]. After the bar is inserted meticulously into the sleeve, the sleeve is filled with non-shrinking high-strength mortar (or other suitable materials such as epoxy resin) [48]. Subsequently, the mortar is poured through the inlet, and air bubbles are removed via the outlet. As shown in Figure 2b, D-cad weld couplers involve filling the sleeve with molten metal instead of mortar. As this method requires large equipment, it is currently not widely used.

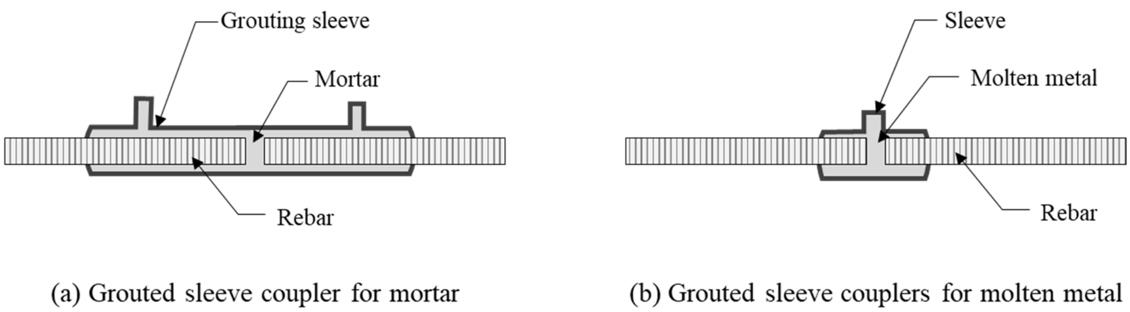

Figure 2. MRC for deformed rebar.

Joints applicable to threaded rebar can be classified into three types: T-threaded couplers, T-epoxy-filled sleeve couplers, and T-grouted sleeve couplers. As shown in Figure 3a, a threaded coupler, which is a general coupler used to join threaded rebars, is applied to threaded rebars [5]. A T-threaded coupler renders construction easier as it does not stretch during joining and is particularly advantageous for joints in columns and beams. When joining threaded rebar, the coupler and threaded rebar may become loose. However, this issue can be resolved as follows: Threaded rebar joints involve twisting the rebar into the coupling (i.e., in a manner resembling a screw), which requires the use of a helical rib rebar. Furthermore, unlike typical deformed rebar, helical rib rebars do not have lateral ribs; instead, they present circumferential ribs in a spiral direction, which resembles a screw. If a coupler that is compatible with the helical rebar is not available, then a dedicated coupler corresponding to the helical rebar manufactured by the respective manufacturer must be used.

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(a) T-threaded coupler (b) T-epoxy-filled sleeve coupler (c) T-grouted sleeve coupler

Figure 3. MRCs for threaded rebar [49].

Screw-fastening types can be classified into torque- and filling-fixation methods. Torque-fixation couplers secure a rock nut on both ends of the coupler to apply an initial tension between the coupler and rebar. The filling-fixation method involves injecting epoxy resin between the rebar and coupler using an air gun after coupling to integrate the joint area. Notably, shear screws can be applied in cases where rebars are embedded in concrete.

As shown in Figure 3b, the T-epoxy-filled sleeve coupler involves the use of epoxy resin, which hardens immediately upon injection, for fixing the rebar and coupler. Unlike gas pressure welding, it does not require large tools, machines, or skilled workers. A dual-cartridge epoxy gun is used as the injection tool. As shown in Figure 3c, T-grouted sleeve couplers are suitable for precast methods. This coupler has a small diameter and length, which can improve workability in both precast component manufacturing and on-site construction tasks. Excluding special couplers, this study analyzes five types of MRCs for deformed rebar (D-grouted sleeve couplers and D-cad weld couplers) and threaded rebar (T-threaded couplers, T-epoxy-filled sleeve couplers, and T-grouted sleeve couplers).

4. Analysis of Different MRC Types

4.1. Selection of Building

A building was selected for the analysis of different types of MRCs. The building is located in Anyang-si, Gyeonggi-do, South Korea, and its specifications are listed in Table 1. The building, which is an RC structure, features 20 floors above the ground and two underground floors.

Figure 4 shows the applied column location and an example of the rebar detail for the seventh-floor plan of the building. The column is the member with the highest count and measures 1000 mm × 800 mm. Different types of columns are listed in Figure A1.

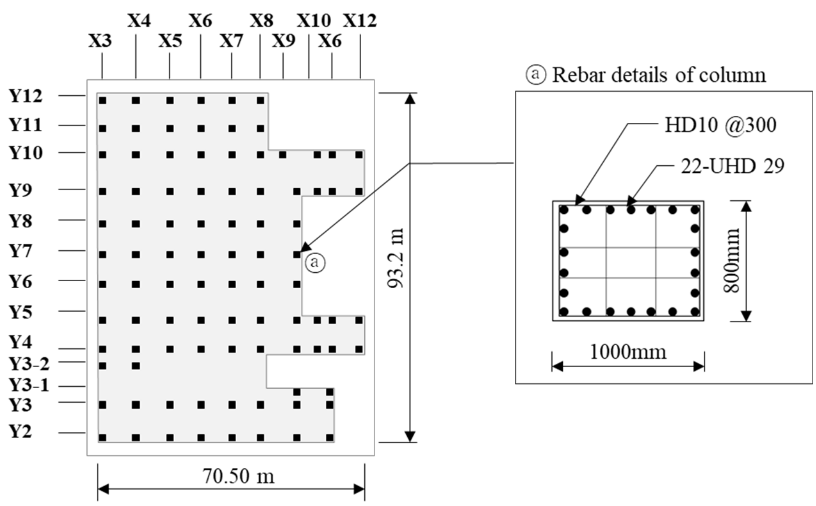

Figure 4. Column location and rebar details of building investigated.

4.2. Analysis of Quality Including Seismic Performance

In this study, five types of MRCs for deformed rebar (D-grouted sleeve couplers and D-cad weld couplers) and threaded rebar (T-threaded couplers, T-epoxy-filled sleeve couplers, and T-grouted sleeve couplers) were analyzed. Table 2 shows the quality analysis of the five couplers. Among the joints for deformed rebar, D-grouted sleeve couplers were significantly affected by the sleeve material, sleeve shape (length and diameter), grout strength, and the bond between the grout and sleeve [36–38,50]. Meanwhile, D-cad weld couplers demonstrated excellent rigidity.

Table 2. Specifications of building for current study.

Description	Details
Location	Anyang-si, Gyeonggi-do, South Korea
Building purpose	Factory building
Site area	10,720 m^2
Building area	6317 m^2
Total floor area	72,916 m^2
Number of floors	B2–20F
Structure	RC structure

Among the joints for threaded rebar, T-threaded couplers enable the realization of high-strength rebar joints based on the principle of screws and specific high-strength cement grout. T-threaded couplers enable rebars of various sizes to be combined. Meanwhile, the T-epoxy-filled sleeve coupler enables the fixing of the rebar and coupler using epoxy, thus allowing rebars of various sizes to be combined. The T-grouted sleeve coupler involves the use of specific non-shrinking inorganic mortar, which achieves stable strength, durability, and fire retardancy upon injection.

The performance quality of the five couplers can be defined based on their seismic performance. Based on our analysis, the ranking from best to worst is the T-epoxy-filled sleeve coupler, T-threaded coupler, T-grouted sleeve coupler, D-grouted sleeve coupler, and D-cad weld coupler. MRCs for threaded rebars exhibit excellent seismic performance, i.e., the rebar outside of the coupler area breaks during disasters such as earthquakes. Specifically, the T-epoxy-filled sleeve coupler offers outstanding seismic performance and can be used for seismic reinforcement.

4.3. Safety Analysis

Table 3 shows the safety analysis of the five couplers. Among the joints for deformed rebars, D-grouted sleeve couplers do not require rebar stretching during connection and facilitate the joining of rebars of different standards, thus offering good constructability and wide applicability in the field. D-grouted sleeve couplers only require a manual mortar gun (i.e., specific equipment is not required), and the large gap between the rebar and steel pipe can easily conceal construction errors. Moreover, the large gap between the rebar and sleeve eases sleeve installation. As the rebar does not expand during joining, joining precast or beam members is advantageous. However, grouted sleeve couplers have a clearance of ±5 mm between the steel pipe and deformed rebar, which implies that their sleeve is larger than those of other couplers—this aspect must be considered during construction. The mortar used for filling is an inorganic non-shrinking mortar, and a strength of 700–1000 kg/cm^2 is required. Hence, precautions must be exercised during construction. D-cad weld couplers are currently not widely used as they require large equipment to heat the filling material at the joint area.

Table 3. Analysis of quality of MRCs, including seismic performance.

Screw Type	Coupler Classification	Quality Analysis	Strength Rank
For deformed rebar	D-grouted sleeve coupler	-Good overall quality. -Determined by factors such as sleeve material, sleeve shape (length and diameter), grout strength, and the bond between the grout and sleeve. -Not suitable for seismic design.	4
	D-cad weld coupler	-Excellent rigidity. -Lacks seismic performance.	5
For threaded rebar	T-threaded coupler	-Good rigidity using grout, i.e., a specific high-strength cement grout. -Excellent seismic performance.	2
	T-epoxy-filled sleeve coupler	-Good quality using epoxy for fixation. -Excellent seismic performance and can be used for seismic reinforcement.	1
	T-grouted sleeve coupler	-Ensures strength, durability, and fire retardancy. -Excellent seismic performance.	3

T-threaded couplers applied to threaded rebars can be cut at any point along their length and combined with another coupler. It takes one coupler and two locknuts to connect the rebar. Additionally, they can be installed rapidly and easily in adverse weather conditions without requiring skilled workers or large machinery. T-epoxy-filled sleeve couplers use epoxy resin, which hardens immediately upon injection, for fixing the rebar and coupler. A dual-cartridge epoxy gun is used as the injection tool. In this method, workability is improved on site without the necessity to tighten locknuts. It was developed for simple and rapid construction and does not require specific equipment or skilled workers. Furthermore, it allows installation to be performed in adverse weather conditions. Meanwhile, T-grouted sleeve couplers offer good workability in both precast component manufacturing and on-site construction tasks. They are applicable even when rebar alignment is off.

4.4. Time Analysis

To perform time (including constructability) analyses for different types of MRCs, we obtained data pertaining to the resources used and measured work times for each coupler (see Table 4. The installation process for each type of MRC was classified based on activity. The resources and work times were measured based on the installation of one coupler. Here, resources refer to the manpower used for each activity, and the installation time of the coupler was estimated by acquiring data. In terms of installation time, the T-threaded coupler required 116.56 min. Only the pure assembly time of the coupler was estimated, i.e., excluding the release agent application, concrete pouring, tie–rebar assembly, accessory insertion, and crane operations.

Table 4. Safety (ease of work) analysis.

Screw Type	Coupler Classification	Safety Analysis	Safety Rank
For deformed rebar	D-grouted sleeve coupler	-Only a manual mortar gun is required, i.e., specific equipment is not required. -Wide gap between rebar and sleeve eases sleeve installation. -Precautions must be exercised during construction.	4
	D-cad weld coupler	-Large equipment required to heat filler material at the joint. -Currently not widely used.	5

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For threaded rebar	T-threaded coupler	-Can be installed in adverse weather conditions. -Fast and simple assembly.	3
	T-epoxy-filled sleeve coupler	-Improves workability on site without having to tighten locknuts. -Simple and rapid construction. -Installation is realizable in adverse weather conditions.	1
	T-grouted sleeve coupler	- Good workability in both precast component manufacturing and on-site construction tasks. - Can be used even if rebar alignment does not match.	2

Based on the second floor of the investigated building (see Figure 4), the installation time for each type of MRC was analyzed, as shown in Table 7. The installation of couplers for one floor was assumed to involve connecting the foundation and the first floor. The total rebar amount for all floors calculated (as presented in Table A1) was applied. In terms of the total work time, the D-cad weld coupler for deformed rebars indicated the least amount of time required, i.e., 496.17 h. In this case, the rebar coupler was applied to two floors as one rebar. Meanwhile, when applied as one rebar for three floors, it was calculated to be 299.09 h. Since the curing period for mortar is not a critical path, it was not considered in calculating the work time.

Table 5. Analysis of installation process for different MRC types.

Screw Type	Coupler Classification	Process	Required Manpower	Work Time (min)	
				Rebar 1ea	Column 1ea
For deformed rebar	D-grouted sleeve coupler	Installing coupler on placed rebar	rebar labor 2	0.21	7.56
		Filling mortar	common labor 1	0.51	18.36
		Curing	-	1440.00	1440.00
			Total		1465.50
	D-cad weld coupler	Installing coupler on placed rebar	rebar labor 2	0.21	7.50
		Filling with molten metal	common labor 1	0.17	5.76
		Cooling	-	120.00	120.00
			Total		133.26
For threaded rebar	T-threaded coupler	Installing coupler on placed rebar	rebar labor 7	0.21	7.56
		Tightening screws	common labor 3	0.25	9.00
		Grouting	common labor 1	0.21	7.56
		Curing	-	0.17	6.12
			Total		16.56
	T-epoxy-filled sleeve coupler	Installing coupler on placed rebar	rebar labor 7	0.21	7.56
		Filling epoxy	common labor 1	0.22	7.92
		Epoxy curing	-	10	10.00
			Total		25.48
	T-grouted sleeve coupler	Installing coupler on placed rebar	rebar labor 7	0.21	7.56
		Tightening screws	common labor 3	0.25	9.00
		Grouting	common labor 1	0.47	16.96
		Curing	-	35.00	35.00
			Total		60.56

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Table 6. Estimated installation times for different MRC types.

Screw Type	Coupler Classification	Work Time (h)
For deformed rebar	D-grouted sleeve coupler	1411.87
	D-cad weld coupler	496.17
For threaded rebar	T-threaded coupler	822.49
	T-epoxy fixation	531.53
	T-grouted sleeve coupler	1142.90

Productivity reflects the relationship between outputs and inputs in the production process [51]. Labor costs typically constitute 30%–50% of the total cost of a project. In the construction industry, labor is typically the dominant or sole resource; thus, labor productivity is generally regarded as the single factor for measuring productivity [52,53]. The American Association of Cost Engineers International [54] defines productivity in the construction industry as the "rate of output per unit of time or effort, usually measured in labor hours." Labor productivity is calculated by summing the products of the labor force and work time required for each activity, as shown in Equation (1). Using the details provided in Table 4 and the work times listed in Table 5, the labor productivity can be calculated as shown in Table 7. In terms of labor productivity, D-cad weld couplers were shown to be the most efficient, with 88.49 man-days, whereas T-grouted sleeve couplers were the least efficient. For reference, applying a T-threaded joint for one rebar on two floors and one rebar on three floors required 275.29 and 187.70 man-days, respectively.

$$LP_T = \sum (L_A \times T_A) \quad (1)$$

LP_T: sum of labor productivity for each activity; *L_A*: number of people involved in each activity; *T_A*: time required for each activity; i: *i*th activity (1,…, n).

Table 7. Labor productivity analysis.

Screw Type	Coupler Classification	Labor Productivity (Unit: man·day)
For deformed rebar	D-grouted sleeve coupler	142.71
	D-cad weld coupler	88.49
For threaded rebar	T-threaded coupler	372.88
	T-epoxy-filled sleeve coupler	259.33
	T-grouted sleeve coupler	412.93

4.5. Cost Estimation

Based on the case presented in Figure 4, the cost for each type of MRC was analyzed (see Tables 7–11). The labor cost rate applied was from the "2023 Second Half Construction Labor Wages Survey Report (Market Labor Rate)", and the material cost and equipment fee were estimated using the "2023 Transaction Prices", the "2023 Construction Standard Estimating System", and actual field applied rates published by the Ministry of Economy and Finance and other professional pricing institutions. The cost of building materials is calculated by multiplying the quantity by the unit price of the material [55]. Comparing the total construction costs, D-grouted sleeve couplers for deformed rebars showed the lowest construction cost at USD 1,486,868. Notably, this method is widely used in actual sites for rebar joints in precast concrete (PC) structures. In this case, the rebar coupler was applied as one rebar per floor.

Table 8. Cost estimation for D-grouted sleeve coupler.

Item		Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	day	266	340.47	90,565
	common labor	day	133	204.10	27,145

Material cost	rebar (UHD 29)	T	1043	774.62	807,774
	coupler	ea	51,559	8.46	436,270
	mortar	t	18.75	211.90	3973
	cut and bend work	t	1043	4.85	5054
Indirect cost					141,674
Total					1,486,868

Table 9. Cost estimation for D-cad weld coupler.

	Item	Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	day	126	340.47	42,899
	common labor	day	63	204.10	12,858
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	coupler	ea	51,559	14.55	749,952
	equipment	ea	1	1026.00	1026
	molten metal	t	17	773.85	13,058
	cut and bend work	t	1043	4.85	5054
Indirect cost					138,773
Total					1,771,394

Table 10. Cost estimation for T-threaded coupler (one rebar per floor).

	Item	Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	day	206.00	340.47	70,137
	common labor	day	103.00	204.10	21,022
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	coupler	ea	51,559	12.31	634,575
	grouting equipment	set	1	320	320
	mortar	t	5.39	221.90	1143
	cut and bend work	t	1043	4.85	5054
Indirect cost					131,017
Total					1,672,388

Table 11. Cost estimation for T-epoxy-filled sleeve coupler.

	Item	Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	day	206.00	340.47	70,137
	common labor	day	103.00	204.10	21,022
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	coupler	ea	51,559	12.31	634,575
	epoxy	t	18.75	89.70	995
	epoxy gun	ea	154	1.17	180
	cut and bend work	t	1043	4.85	5054
Indirect cost					130,878
Total					1,579,455

Additionally, as shown in Tables 12 and 13, when a T-threaded coupler was applied for one rebar over two floors, the cost was estimated to be USD 1,287,180, whereas for one rebar over three floors, it was estimated to be USD 1,159,737. To apply T-threaded couplers to one rebar over three floors and one rebar over two floors, planning must be performed during the design drawing stage. Therefore, to achieve economic efficiency by applying T-threaded couplers, cost analysis should be conducted at the project planning stage, followed by design and construction.

Table 12. Cost estimation for T-grouted sleeve coupler.

Item		Unit	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	Day	501	340.47	170,405
	common labor	Day	257	204.10	52,535
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	coupler	ea	51,559	12.31	634,575
	scaffolding (600 × 500 × 1500)	ea	1	833	833
	grouting equipment	ea	1	833	833
	mortar	t	16.48	211.90	3492
	cut and bend work	t	1043	4.85	5054
Indirect cost					142,418
Total					1,817,920

Table 13. Cost estimation for T-threaded coupler (one rebar over two floors).

Item		Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	day	122	340.47	41,537
	common labor	day	61	204.10	12,450
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	coupler	ea	25,780	12.31	317,287
	scaffolding (600 × 500 × 1500)	ea	1	833	833
	grouting equipment	ea	1	833	833
	mortar	t	2.70	211.90	571
	cut and bend work	t	1043	4.85	5054
Indirect cost					100,839
Total					1,287,180

4.6. CO_2 Estimation

Using the labor, material costs, and indirect costs estimated from Tables 7–11, CO_2 emissions were calculated, as shown in Table 14. Here, CO_2 emissions corresponding to direct costs were calculated using the actual labor input and electricity use. Additionally, CO_2 emissions corresponding to indirect costs were calculated using the actual lighting input and heating use. Comparing the resulting CO_2 emissions, the D-grouted sleeve coupler showed the lowest emission at 4928.49 T-CO_2. However, the CO_2 emission by T-threaded couplers for one rebar over two floors and one rebar over three floors were 4761.50 and 4400.31 T-CO_2, respectively. Therefore, the T-threaded coupler for one rebar over three floors resulted in the lowest CO_2 emissions.

Table 14. Cost Estimation for T-threaded coupler (one rebar over three floors).

Item		Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar labor	day	96	340.47	32,685
	common labor	day	48	204.10	9797
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	coupler	ea	17,186	12.31	211,525
	scaffolding (600 × 500 × 1500)	ea	1	833	833
	grouting equipment	ea	1	833	833
	mortar	t	1.80	211.90	381
	cut and bend work	t	1043	4.85	5054
Indirect cost					90,855
Total					1,159,737

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5. Proposed Data-Driven MRC Selection Process

As shown in Figure 5, the MRC selection algorithm comprises six steps. All stages can be analyzed using a database (DB). This implies that data pertaining to the MRC type, related regulations, design documents, unit price, and CO_2 emissions are required, and they are provided at each stage.

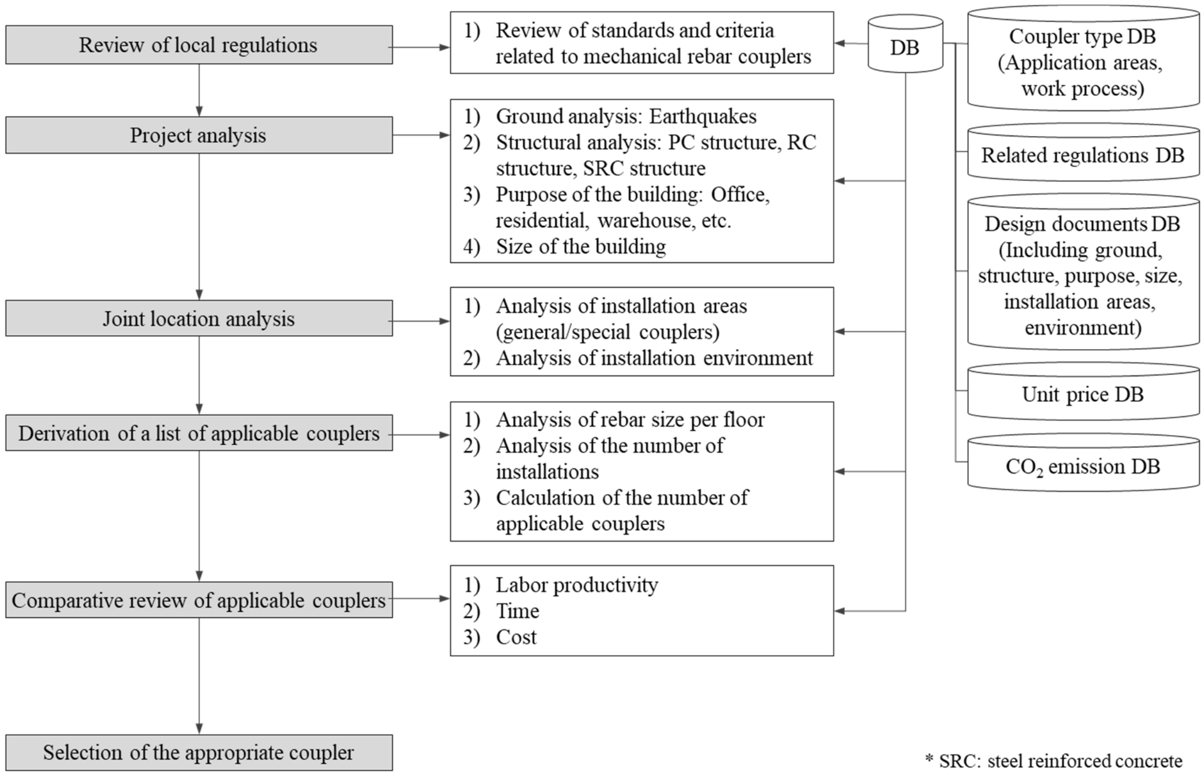

Figure 5. Data-driven MRC selection algorithm.

(1) Review of local regulations

The criteria for coupler selection apply to all coupler types based on the mechanical coupler standards and regulations of each country [5]. Table 15 shows the regulations for Eurocode 2 [56], ACI 318–19 [57], UBC-97 [58], Caltrans SDC [59], AASHTO LRFD [60], and Korean Industrial Standards [61]. Eurocode 2 [56] does not provide specific standards for mechanical couplers [54]. According to section 25.5.7.1 of ACI 318–19 [57], Type 1 mechanical bar splices must satisfy a minimum of 1.25 fy in compression, and according to section 18.2.7.1, Type 2 must fulfill the requirements of Type 1 mechanical splices and represent the specified tensile strength of the rebar [5,58].

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Table 15. CO_2 emission calculation (unit: T-CO_2).

Classification	For Deformed Rebar		For Threaded Rebar				
	D-Grouted Sleeve Coupler	D-Cad Weld Coupler	T-Threaded Coupler (One Rebar over One Floor)	T-Threaded Coupler (One Rebar over Two Floors)	T-Threaded Coupler (One Rebar over Three Floors)	T-Epoxy-Filled Sleeve Coupler	T-Grouted Sleeve Coupler
Labor	98.42	46.62	76.22	45.14	35.52	76.22	158.73
Material use	4683.63	5824.75	5734.57	4694.34	4347.46	5753.44	5712.19
Electricity use	106.29	50.35	82.32	48.75	38.36	83.08	168.25
Lighting, and heating use	40.14	19.01	31.09	18.41	14.49	31.24	64.11
Total	4928.49	5940.73	5847.97	4761.50	4400.31	5943.98	6103.29

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According to section 1912.14.3.4 of UBC-97 (1997), mechanical joints must provide 1.25 fy of a rebar in tension or compression, and according to section 1921.2.6.1, no splices are allowed at a vertical distance exceeding 24 inches (610 mm) [58]. Caltrans SDC (2013) allows "service" and ''ultimate" couplers to be classified based on the deformation capacity [1,57]. Meanwhile, AASHTO LRFD (2014) only allows couplers that can express a minimum strength of 1.25 times the yield strength of the rebar [60]. Moreover, in South Korea, according to Korean Industrial Standards KSD 0249 (2019), couplers that exceed 1.25 times the minimum yield point of the rebar or the tensile strength of the rebar are allowed. For the case site shown in Table 1, South Korea's KSD 0249 is applied [61].

(2) Project analysis

Ground conditions must be analyzed when examining structures; in particular, earthquakes must be considered when examining structures in Indonesia and Japan, where earthquakes occur frequently. Generally, current bridge and building design regulations stipulate the use of mechanical splices in the plastic hinge zones of ductile members in areas susceptible to earthquakes [57,59,60]. For RC bridges and building members subject to earthquake loads, tension–compression couplers are necessitated to connect vertical rebars because the members resist periodic shaking [1]. Additionally, the building structure (e.g., PC, RC, and SRC structures, etc.) must be analyzed, and the possibility of cutting rebars for two floors per section or three floors per section based on the building's use (offices, residences, warehouse facilities, etc.) should be assessed. Moreover, the applicability of MRCs based on the building size should be reviewed. This building is an RC structure, and the floor height for the 7th to 18th floors is 3800 mm. It can be installed with couplers for one rebar per floor or one rebar per two floors.

(3) Joint location analysis

As shown in Figure 1, couplers can be classified into those for deformed and threaded rebars couplers. Couplers for deformed and threaded rebars are applied at columns and beams in general buildings, whereas special couplers are installed in areas other than general building joints such as footing beams and D-walls. Hence, the joint position must be analyzed based on the installation environment, and the appropriate coupler must be used. Moreover, special couplers can be classified into those used for welding fixed rebar units, concrete embedding, and anchoring. In this study, a special coupler was applied to the column members of the investigated building.Derivation of applicable coupler list

After analyzing the coupler types, a list of applicable couplers was derived. The rebar sizes for each floor of the investigated building were analyzed, and areas where rebar joints of different sizes were connected were identified. The number of couplers to be installed was analyzed, and the number of applicable couplers was summed. In this study, lap splices and mortar filling (two floors per section) were assumed.

(5) Comparative review of applicable couplers

The advantages and disadvantages of couplers were compared in this study in terms of labor productivity, time, and cost. When lap splices were applied, the cost was estimated to be USD 1,530,209, as shown in Table 16. Applying the cost calculated for a T-threaded joint of one rebar over two floors from Table 12 can result in a cost reduction of 16.57%.

Table 16. Regulations of mechanical couplers by country.

Code	Provisions
Eurocode 2 [56]	-No criteria are provided.
	-25.5.7.1: mechanical bar splices should develop at least 1.25 fy of bars in tension or compression.
ACI 318–19 [57]	-18.2.7.2: except for Type 2 mechanical splices on Grade 60 bars, mechanical splices cannot be used in (a) within 2 × member depth from the column or beam face for specific moment frames or from critical sections. Type 2 mechanical

UBC 1997 [58]	splices on Grade 60 bars are permitted at any location but not in < 0.5 h from the joint's face. -1912.14.3.4: mechanical splices should provide 1.25 fy of bars in tension or compression. -1921.2.6.1: no splices are permitted within a vertical distance of 24 inches (610 mm).
Caltrans SDC [59]	-"Service" and "ultimate" couplers classified based on deformation capacity are allowed.
AASHTO LRFD [60]	-Only couplers that can express a minimum strength of 1.25 times the yield strength of the rebar are allowed.
Korean Industrial Standards-KSD 0249 [61]	-Couplers that exceed 1.25 times the minimum yield point of the rebar or the tensile strength of the rebar are allowed.

Table 17. Cost estimation for lap splices.

Item		Units	Quantity	Unit Price (USD)	Amount (USD)
Labor cost	rebar worker	day	944	340.47	321,336
	common labor	day	472	204.10	96,315
Material cost	rebar (UHD 29)	t	1043	774.62	807,774
	lapping	ea	227	774.62	175,528
	lapping tool	ea	50	15	769
	embedded steel	ea	3	758	2273
	cut and bend work	t	1307	4.85	6336
Indirect cost					119,878
Total					1,530,209

Based on the previously estimated results, the productivity, duration, and construction costs between lap splices and T-threaded couplers were compared, as shown in Figure 6. Compared with lap splices (the conventional method), T-threaded couplers (for two floors per section) indicated 56% more efficient labor productivity, 15% shorter construction time, 17% lower costs, and 26% lower CO_2 emission. However, these values can vary depending on the site conditions and assumptions.

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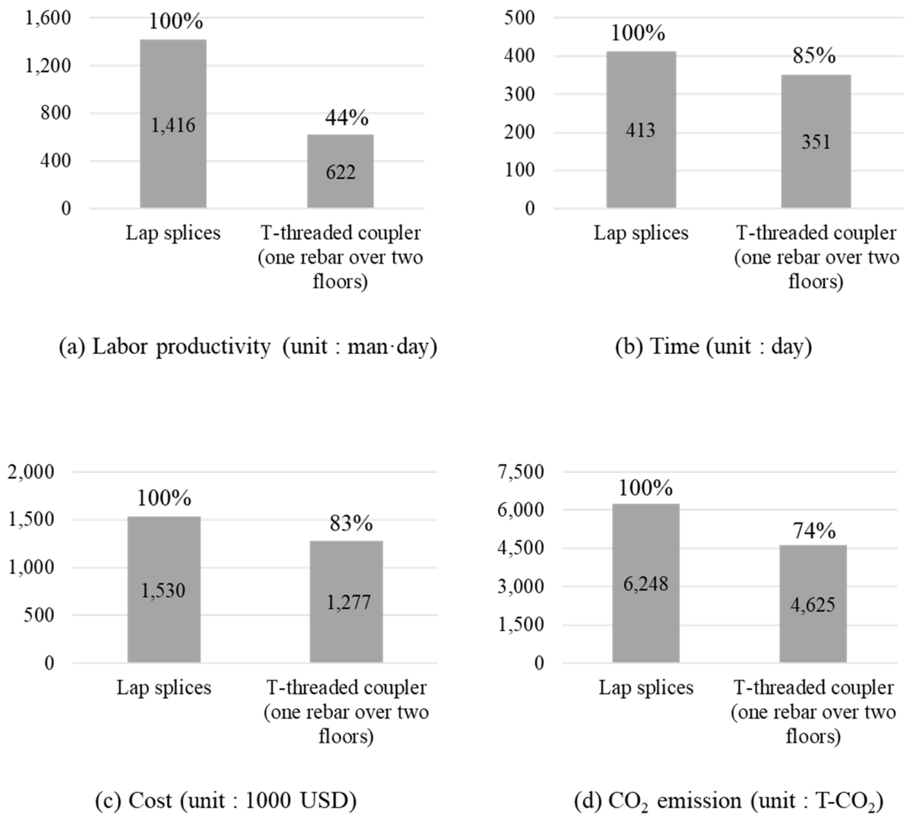

Figure 6. Comparison for lap splices and T-threaded coupler (for one rebar over two floors).

(6) Selection of Appropriate Coupler

The advantages and disadvantages of couplers applicable to the investigated building were compared, and a suitable coupler was selected. In this study, a T-threaded coupler (for two floors per section) was applied, owing to its superiority in terms of labor productivity, duration, and cost compared with lap splices. When necessary, the feedback routine was performed to return to stages such as "review of local regulations" and "project analysis", and the appropriate coupler was reselected. Subsequently, a cost-effective T-threaded coupler (for one rebar over two floors) was selected.

6. Discussion

MRC selection can vary based on key factors such as earthquake vulnerability, environmental conditions, and costs. Among the influencing factors, environmental conditions include temperature, humidity, and corrosiveness; earthquake vulnerability includes the site's topography, ground conditions, and regional earthquake risk; and costs are categorized into purchasing and installation costs. Considering these factors, among the five types of MRCs, the T-epoxy-filled sleeve coupler was shown to possess the best quality owing to its excellent seismic performance and resistance to temperature, humidity, and corrosion. However, because of its high purchase and installation costs, it cannot be readily applied in the field. Therefore, T-epoxy-filled sleeve couplers should be compared with other MRCs in future studies to enhance their field applicability and devise cost reduction strategies. Additionally, comparative studies pertaining to MRCs should be conducted based on the purpose and characteristics of different buildings.

D-cad weld couplers are not currently widely used as they require large equipment to heat the filler at the joint; nonetheless, they should be investigated further through technological development. In regard to threaded couplers, their joint state can be inspected easily, and their joint strength is stronger than the strength of the rebar material. Under the same conditions as those presented in Table 5, the time required for the shell coupler should be 40 h. However, the compatibility of the shell coupler with the rebar shape is low, and the rebar can slip; thus, subsequent actions such as mortar filling are necessitated. Under different rebar standards, mortar filling is required, and the constructability of spiral and circular tie rebars is deteriorated. Therefore, the shell coupler was excluded when conducting this study. Additionally, a composite coupler combines various mechanical splicing techniques that are primarily used for modular construction, such as for constructing PC components. The limitations of labor-intensive construction production methods [62] can be improved. When using threaded rebar, one can change the application method on site based on the design. This implies that design changes can be accommodated easily during construction as various couplers can be flexibly used with one type of rebar.

Recently, the integration of mechanical splicing in precast RC structures has increased [42,63–66]. For PC structures, beams and columns are manufactured in factories with inserted rebars, and production errors can render accurate rebar positioning difficult. Therefore, using MRCs with mortar filled through sleeves is useful as it avoids the necessity of reproducing components. For large logistics centers and IDC centers designed with a floor height of approximately 10 m, which is equivalent to approximately three floors of a general building, the same conditions as those for three floors per section are applied. Furthermore, mechanical couplers are used to join rebars of PC components, and high-strength expansive cementitious grout is poured to connect precast beams with columns [63,64]. Liu et al. (2018) proposed a half-threaded half-grouted sleeve for connecting rebars [67].

Meanwhile, Huang et al. (2020) investigated the application of sleeves filled with resin (instead of grout) for FRP rebars [68]. The performance of FRP structures has been evaluated in various studies via field applications [69–72], and the bond between concrete and FRP rebar is a significant concern because it controls the load-bearing capacity and ductility as well as the limits of deflection and crack width in RC structural members [73,74]. Additionally, the use of FRP reinforcing materials can reduce future maintenance and repair costs arising from increased corrosion resistance and the durability of concrete structures [75,76]. However, FRP rebars exhibit higher tensile strengths but weaker bond strengths compared with steel rebars, thus requiring complex regulations for lap lengths. This results in complicated rebar splicing in concrete members (beams and columns) where laps are provided. Moreover, securing the concrete cover thickness is challenging, which renders it more effective to apply MRCs to standard rebars than to FRP rebars.

7. Conclusions

In this study, five types of MRCs for deformed rebars (D-grouted sleeve couplers and D-cad weld couplers) and threaded rebars (T-threaded couplers, T-epoxy-filled sleeve couplers, and T-grouted sleeve couplers) were analyzed. Data pertaining to each type of MRC were obtained, and their characteristics were analyzed in terms of their construction method, which included the duration of installation, quality, safety, cost, and CO_2 emissions, based on the shape and structural characteristics of the reinforcing bars. Furthermore, selection algorithms for suitable couplers were analyzed via classification based on the characteristics of the structure. The conclusions inferred from this study are as follows:

First, the quality performance of the five couplers can be defined based on their seismic performance. Based on our analysis, the ranking from best to worst is the T-epoxy-filled sleeve coupler, T-threaded coupler, T-grouted sleeve coupler, D-grouted sleeve coupler, and D-cad weld coupler. MRCs for threaded rebars exhibit excellent seismic performance, i.e., the rebar outside of the coupler area breaks during disasters such as earthquakes. Specifically, the T-epoxy-filled sleeve coupler presents outstanding seismic performance and can be used for seismic reinforcement.

Second, when a T-threaded coupler was applied for one rebar over two floors, the cost was estimated to be USD 1,287,180, whereas for one rebar over three floors, it was estimated to be USD 1,159,737. In other words, the T-threaded coupler for threaded rebars, when applied for one rebar over three and two floors, resulted in significant cost savings. For one rebar per floor, D-grouted sleeve couplers for deformed rebars were shown to be the most cost effective. For one rebar and one column member, the curing period was included in estimating the construction time. However, when assembling couplers for the entire column's rebar, the curing time constituted the assembly time and was not considered a critical path; therefore, it was excluded in the estimation.

Third, when designing for one rebar per floor, planning must be performed from the design stage to apply one rebar over two or three floors. Therefore, to achieve economic benefits by applying T-threaded couplers to threaded rebars, cost analysis should be conducted at the project planning stage, followed by design and construction.

Fourth, using a data-driven MRC selection algorithm, an appropriate MRC was derived. Compared with using lap splices (the conventional method), using the T-threaded coupler (for one rebar over two floors) resulted in 56% more efficient labor productivity, 15% shorter assembly time, 17% lower costs, and 26% lower CO_2 emission. Thus, using the T-threaded coupler (for two floors per section) was more efficient than using lap splices. However, the results can vary for sites with different conditions.

Fifth, using the data-driven MRC selection algorithm allows one to select MRCs rapidly and easily on site. The developed model presents the necessary data and enables data management. Hence, using this model, one can easily and promptly respond to frequent design changes during project execution and apply the appropriate MRC based on the situation.

This study shows that couplers suitable for site conditions can be selected in the early stages of construction based on the reinforcing bar shape and structural characteristics. Because the results obtained in this study are based on acquired data, applying them to different types of buildings and other structural components such as beams and slabs may yield different results. Although this study was conducted on the columns of a factory building, further studies should be performed on different types of buildings and other structural components such as beams and slabs. Additionally, studies should be performed to specify the MRC selection process and apply it to case studies, and the characteristics of special couplers should be examined.

Author Contributions: J.L.: Methodology, formal analysis, investigation, validation, writing—original draft preparation, writing—review and editing, resources, and funding acquisition. S.K.: Conceptualization, methodology, investigation, resources, writing—review and editing, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data sharing is not applicable to this paper.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that may have influenced the work reported in this paper.

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Appendix A

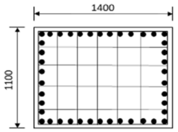
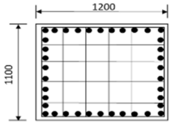
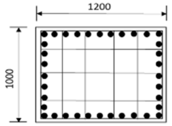
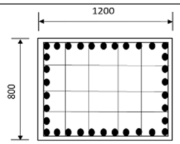
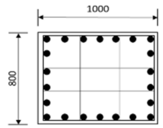
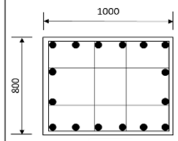
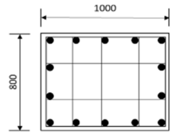
Floors		B2-B1	F1	F2-F3	F4-F6	F7-F8	F9-F12	F13-F20
C14								
Concrete strength (fc)		35	35	35	35	35	35	35
Dimension		1400 x 1100	1200 x 1100	1200 x 1000	1200 x 800	1000 x 800	1000 x 800	1000 x 800
Reinforcement		42 – UHD29	38 – UHD29	36 – UHD29	34 – UHD29	22 – UHD29	16 – UHD29	14 – UHD29
Hoops	Both ends	HD10 @300	HD10 @150	HD10 @150	HD10 @150	HD10 @150	HD10 @150	HD10 @150
	Center	HD10 @300	HD10 @300	HD10 @300	HD10 @300	HD10 @300	HD10 @300	HD10 @300

Figure A1. Rebar arrangement of columns.

Table A1. Total rebar amount for all floors.

Floor	Floor Height (mm)	Lapping Length (mm)	Number of Rebars (ea)	Number of Columns (ea)	Total Quantity (ton)
B2	3700	24.86	42	145	114.3294
B1	4600	24.86	42	118	115.5209
F1	4600	24.86	38	109	96.54715
F2	5600	24.86	36	101	103.0781
F3	5600	24.86	36	101	103.0781
F4	5600	24.86	34	101	97.35152
F5	5600	24.86	34	101	97.35152
F6	6000	24.86	34	101	104.2745
F7	3800	24.86	22	93	39.44137
F8	3800	24.86	22	41	17.38813
F9	3800	24.86	16	44	13.57122
F10	3800	24.86	16	44	13.57122
F11	3800	24.86	16	44	13.57122
F12	3800	24.86	16	44	13.57122
F13	3800	17.05	14	32	8.61859
F14	3800	17.05	14	32	8.61859
F15	3800	17.05	14	32	8.61859
F16	3800	17.05	14	32	8.61859
F17	3800	17.05	14	32	8.61859
F18	3800	17.05	14	32	8.61859
F19	4400	17.05	14	32	9.973342
F20	4400	17.05	14	26	8.10334
Total			516	1437	1012.434

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