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Seismic Pushover Analysis of Global Emulative Response of Precast Reinforced Concrete Frames with Dextra Groutec Couplers

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Abstract The effects of Dextra Groutec couplers on the global performance of precast reinforced concrete frames are investigated by comparing the performance criteria of conventional RC structures to that of the said structures such that precast elements are connected end-to-end using these couplers. As couplers provide continuity of the reinforcement, precast elements that are connected using this mechanism can perform as a unit, and the entire structural system can be considered emulative as long as the structural performance is comparable to that of the conventionally designed cast-in-place. Dextra couplers inherently have lower strain compared to reinforcing rebar, affecting the global performance of a structure if placed within critical regions such as near the beam-column connection. The present study is conducted therefore to perform a comparative study to determine the effect of these couplers on the emulative behavior of the precast frames to the cast-in-place frames by considering the following factors: Coupler location, Dextra Groutec Coupler size and length, and the story height of the frame. Static pushover analysis of 30 models is carried out using the finite element software, Seismostruct. Pushover curves are compared based on the three criteria such as global ultimate displacement, displacement ductility, and energy dissipation. The results revealed that the Dextra Groutec Couplers reduce the capacity of the precast frame according to the three performance criteria. Hybrid configuration, where the bottom part is CIP and the upper part is precast connected by couplers is found to be the most viable option to obtain an emulative response. The longer and bigger Dextra Groutec coupler, S28 also manifested more inferior performance compared to S25. Lastly, the height of the structure is not a strong factor in the emulative response except for the hybrid and coupler placed at D distance away from the joint face configurations.

Keywords Couplers, Precast, Pushover, Emulative, Seismostruct

1. Introduction

Precast concrete is a type of concrete that is prepared off-site, usually in a controlled environment. The casting and curing of concrete are done on a plant and are transported to a site for erection. Precast concrete structures have long been utilized in the global construction industry for several decades because of the numerous advantages they offer. Reduction of on-site construction duration and manpower implies that project costs will be lessened. Prefabricated elements' quality can also be improved since monitoring of the concrete's curing, temperature, formwork, and mix design is properly executed. Precast construction also promotes a safer construction platform among workers due to reduced formworks and wastages resulting in a cleaner working environment [1].

Because of their versatility, precast structures have been widely used as culverts, catch basins, curb inlets, and nonstructural walls. In light of recent construction developments, countries with moderate to high seismic occurrence including Japan, New Zealand, the USA, Chile, and Italy already adopt precast concrete structures as moment-resisting elements in mid-rise and high-rise structures by utilizing state-of-the-art construction methodologies.

The seismic behavior of a building built with earthquake-resisting precast concrete column and beam elements highly depends on the performance of the precast-to-precast connection: its stiffness, ductility, and strength characteristics [2]. In general, precast concrete construction can be categorized into two types: emulative and jointed.

Emulative detailing refers to the process of designing and detailing the precast structure in a way that the whole structural system's performance in terms of energy dissipation, ductility, and strength is comparable to a conventional cast-in-place structure. In designing a cast-in-place structure, the structural system is assumed to behave monolithically as a unit. On-site concrete pouring is performed section by section forming construction joints, nevertheless, the structure still performs as a unit because of rebar continuity. The same principle is applied to emulative precast concrete. In the case of precast beam-to-column connection, joints are usually at the ends of the elements. The significant difference between cast-in-place and emulative precast structures involves field connection and assemblage of the precast elements. But the approach for the structural analysis and design of the structural beams and columns essentially stays the same [3]. The second type of precast concrete construction is the jointed construction which primarily uses unbonded post-tensioning steel as reinforcement in moment frames. In this study, an emulative precast structure composed of precast beams and columns is the focus.

For a precast structure to be considered emulative, the continuity of the concrete and longitudinal rebars must be complied with. The continuity for concrete is provided by the use of either grout or cast-in-place concrete on the connection region. For the longitudinal bar connections, several methods are available such as using dowels, sleeves, bearing pads, bolts and plates, and couplers.

A mechanical Coupler utilized as a precast beam-to-column connector is used as the rebar connector in this study. It is made of a steel sleeve used to join segments of rebar to transfer forces from one steel rebar to another. This mechanical device can be used instead of lap splicing and does not rely on concrete for load transfer. Its easy installation reduces labor and manpower costs, and increases construction safety. It also reduces rebar congestion compared to conventional lap splicing, and a maximum of 8% steel-concrete ratio can be attained if there is a limitation on the column/beam sizes [4].

In precast-to-precast application, only a grout-filled coupling sleeve/grouted coupler is acceptable for use according to ACI Committee 439 [5]. Dextra Groutec Couplers, in particular, is the brand of coupler used in this study. Vertical connection and horizontal application using this brand of mechanical coupler utilize minimal formworks and mortar as shown (Figure 1A and 1B).

Numerous experimental studies involving mechanical couplers are conducted to understand the behavior of a precast beam-to-column connection using couplers under seismic loadings. Large-scale precast concretes adjoined by couplers are fabricated to conduct experimental studies on the effect of mechanical splices in structures. In the accelerated bridge construction (ABC) research program, half-scaled precast columns connected to precast cap beams using full-grouted couplers under cyclic quasi-static loadings was investigated by Ameli [6]. Apparently, displacement ductility is reduced for structures with couplers compared to the control specimen, which is cast-in-place. A better hysteresis response is obtained when the couplers are placed in the cap beam rather than in the plastic hinge region. Localized cracking is also evident in the precast element with couplers at column plastic hinges unlike in the cast-in-place specimen with ideal, well-distributed flexural cracks. In a similar study conducted by Haber [7], the location of these mechanical splices is taken into consideration wherein pedestals that are 0.5D away from the column-footing joint are added to some test specimens. The overall assessment is that an altered plastic hinge mechanism is present due to the mechanical splices and the precast pedestal, which in turn affected the drift ratio. It was observed that plastic rotation of columns occurred within the upper part of the footing. Hence, for the specimen with grouted coupler placed 0.5D away from the base of the column, the plastic deformation's shifting to footing resulted in reduced displacement ductility and drift capacity.

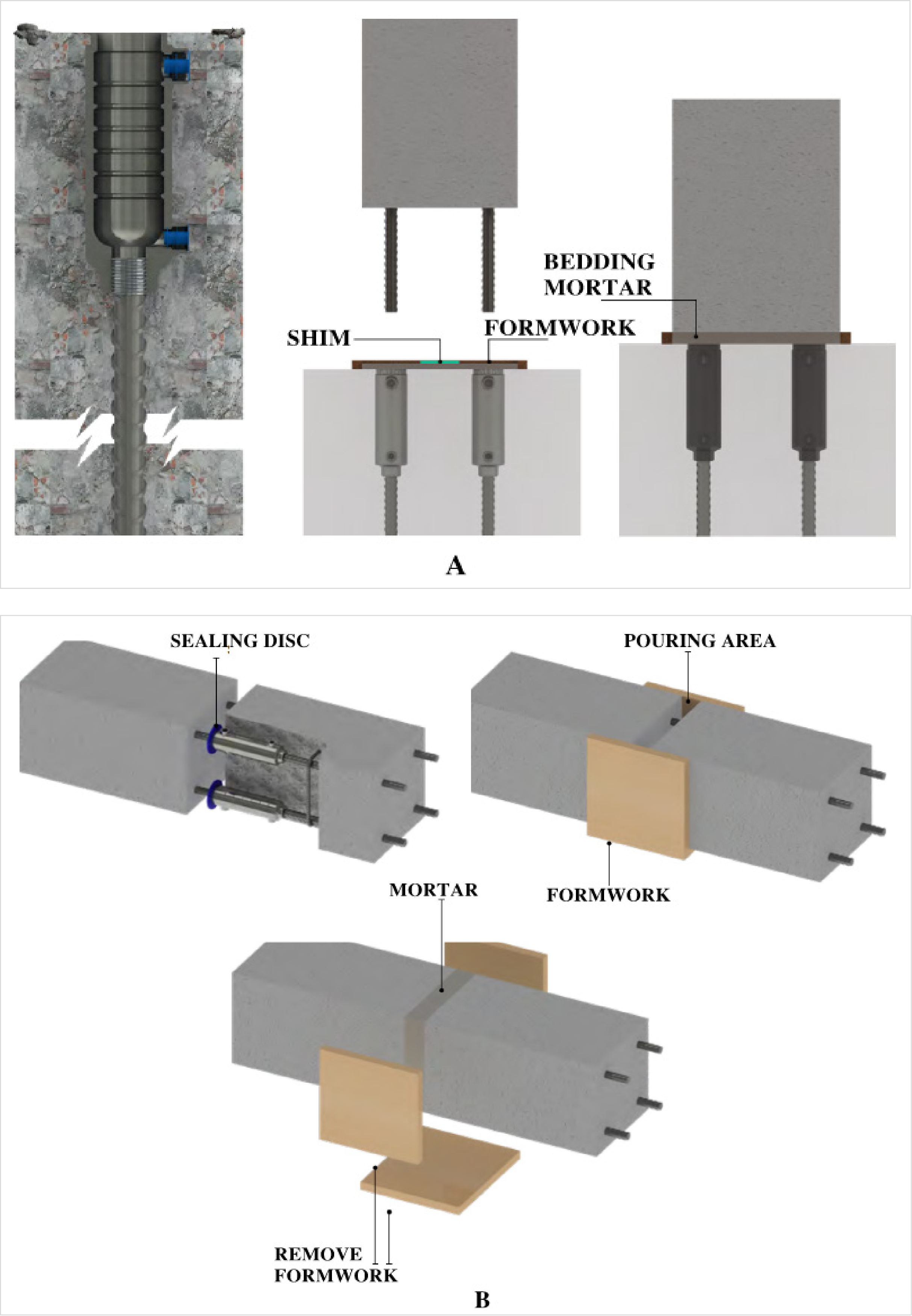


Figure 1. Vertical (A) and Horizontal (B) Connection

Despite numerous experimental studies conducted to understand the coupler behaviors employed on columns/beams, there is still a shortfall of studies in terms of the mechanical splice's effect on the whole structure. Experimental procedures are costly, thus analytical studies are preferred. In the case of mechanical couplers, since their mechanical properties such as the constitutive stress-strain model vary from one manufacturer to another, Haber [8] proposed simplified modeling for mechanical splices wherein the stress-strain model of the reinforced steel bar is scaled-down to achieve the desired response of the coupler. Another parametric study headed by Tazarf [9] was carried out to develop a simple design equation accounting for coupler effects on displacement ductility capacity of structures. This study has the same idea as Haber's in terms of the scaled-down mechanical properties of couplers. However, a new key parameter is introduced which is the rigid length factor, β. During tension action, it is anticipated that only a region of the coupler imparts on the deformation of the splice whilst the remaining part, which is the rigid region, remains unchanged and rigid due to the relatively larger diameter of the coupler compared to the rebar. This rigid region is defined by the rigid length factor multiplied by the coupler length ($\beta * L_{sp}$), wherein $\beta < 1.0$. Thus, lower strain in the coupler regions is manifested compared to the reinforcing bar at the same tensile force (Figure 2).

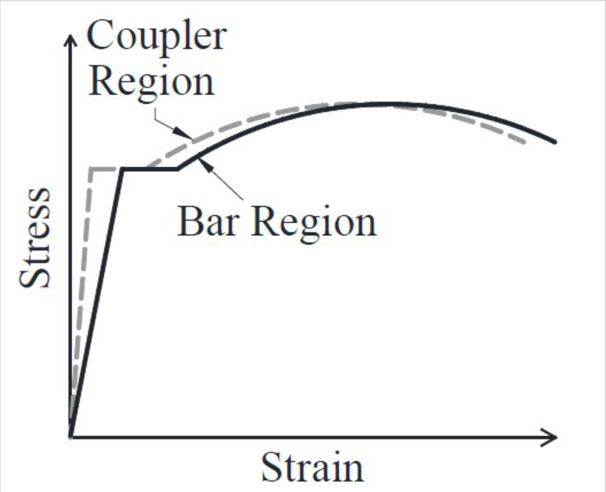


Figure 2. Stress-Strain Model of Mechanical Bar Splice and Control Bar

The main objective of this study is to determine Dextra Groutec couplers' effect on structures in terms of global ultimate displacement, displacement ductility, and energy dissipation based on different coupler locations, coupler size, and story height. The sub-objectives include: (1) to gather cyclic/monotonic loading experimental data of Dextra Groutec Coupler connecting Philippine rebars (2) to determine the Dextra Groutec coupler's design parameters (3) to perform software validation/verification by modeling a single precast column connected using a grouted coupler based on an experimental study (4) to model and analyze different structures incorporating couplers using the validated software, Seismostruct (5) and to perform a comparative analysis among precast structures connected by Dextra Groutec couplers regarding their global emulative performance, in comparison to conventional structures.

2. Methodology

This study is focused on assessing the special moment-resisting frames incorporating mechanical couplers in terms of their global performance and emulative response to their conventional counterparts, by performing static pushover analysis. This section presents the relevant variables in the study and how they affect the emulative performance of precast structures. Moreover, theories supporting this research are discussed comprehensively to support the analysis and help interpret results and generalizations. Lastly, the methodology including the analytical process is discussed diligently including actual screenshots of analytical procedures, and the outline of the whole process is presented using a flowchart.

2.1. Conceptual Framework

This paper intended to scrutinize and evaluate if moment-resisting structures in the high seismic region (zone 4) omprising precast columns and beams can emulate the behavior of conventional "cast-in-place" erections specifically by utilizing mechanical couplers as the structural connectors. The performance of the precast structure in terms of its emulative response to the conventional ones is evaluated based on several factors including the coupler parameters and the assemblage of these mechanical splices in the beam-column joints. Precast connectors are placed near the structural beam-column joints, thereby, Type 2 mechanical couplers, which are designed to avoid splice failure and are capable of developing the tensile strength of the spliced bars will be used in this study. Under Type 2 couplers, only grout-filled coupling sleeves are applicable for use in precast to precast connection.

The length of the coupler affects the value of the rigid region of the device [9]. In this paper, two Dextra Groutec coupler types, S25 and S28 will be used to determine if there will be some changes in the stress-strain curve results if the length and diameter of couplers will change.

The position of couplers along the span of the precast columns/beams is crucial in developing an emulative behavior of the precast structure. The researcher wants to know if there is a relationship between the distance of the coupler to the face of the beam-column connection and the pushover curve of the structures.

And since it is within the interest of the researcher to produce an emulative precast structure using couplers, a combination of cast-in-place (half-bottom) and precast using couplers (half-top) was also explored to determine if this will be a viable option to achieve an emulative response.

Aside from several factors mentioned, the emulative response of the precast structure might also be affected by the structure's story height. As the height of the structure increases, the period (T) increases which absorbs larger transient forces. Hence, the performance of the structures with coupler must be scrutinized if it affects the pushover curve with a significant amount for higher stories compared to lower stories.

2.2. Theoretical Framework

Table 1. Performance Criterion for Emulative Precast Concrete Connection

Displacement Ductility Capacity of CIP Structure (µCIP)	Displacement Ductility Capacity of Emulative PC Structure (µCIP)
≤ 5	At least equal to µCIP
> 5	Greater of:
	(a) 0.9µCIP
	(b) 5

The approach for modeling a precast element with a coupler as a connector is the same as with the modeling of a cast-in-place element, except the parameter for the coupler region is modified, based on the validation modeling carried out by Haber [7]. In his study, the column element was modeled using the fiber section approach having 4 integration points. Nonlinear static pushover analysis was conducted and the result of the pushover curve is very close to the actual force-displacement curve of the experimental column. Hence, the analytical models carried out in this study has a similar approach to Haber's and Hashib's.

For the emulative design to be acceptable, performance criteria relative to the ductility of CIP/conventional structure shall be complied with. The acceptance criterion was established by Tazaarf [9] for emulative bridge design and will be used for the evaluation of the emulative response of ho structures under this research (Table 1).

2.3. Methodological Framework

2.3.1. Experimental Validation of Reinforced Concrete Column with Coupler

Before proceeding with the modeling of the structures, the researcher first validated the coherence of this concept by replicating a suitable experimental study involving grouted couplers and compared the results of the load-displacement curve of the experiment to that attained using the computer program Seismostruct.

The validation is conducted for columns incorporating mechanical couplers using the experimental data of Haber [7] in the study "Seismic Performance of Precast Columns with Mechanically Spliced Column-Footing Connections". Figure 3 shows the configuration of the precast column.

Material property for concrete is assigned as "mander", a uniaxial nonlinear constant confinement model. A constant confining pressure throughout the entire stress-strain range provided by the lateral transverse reinforcement is incorporated in this material type. The tensile resistance of concrete is assigned as zero to prevent the instability of the analysis. For the longitudinal rebars and coupler, the constitutive models are defined using the "Menegotto-Pinto model with Monti-Nuti post elastic buckling" material type, which is capable to characterize post-elastic buckling behavior of reinforcement bars under compression. Assignment of section configuration including the size and number of rebars is the same for segments with and without couplers. The only difference is the material model used for the reinforcement bar, which is previously defined for the main bar and couplers.

Inelastic displacement-based distributed plasticity frame element with 300 fiber sections is considered the element type to be used. The length of the section with couplers is relatively shorter, hence this type of element class is more appropriate for a more refined mesh and to produce higher accuracy in the case of higher-order distributions of deformations.

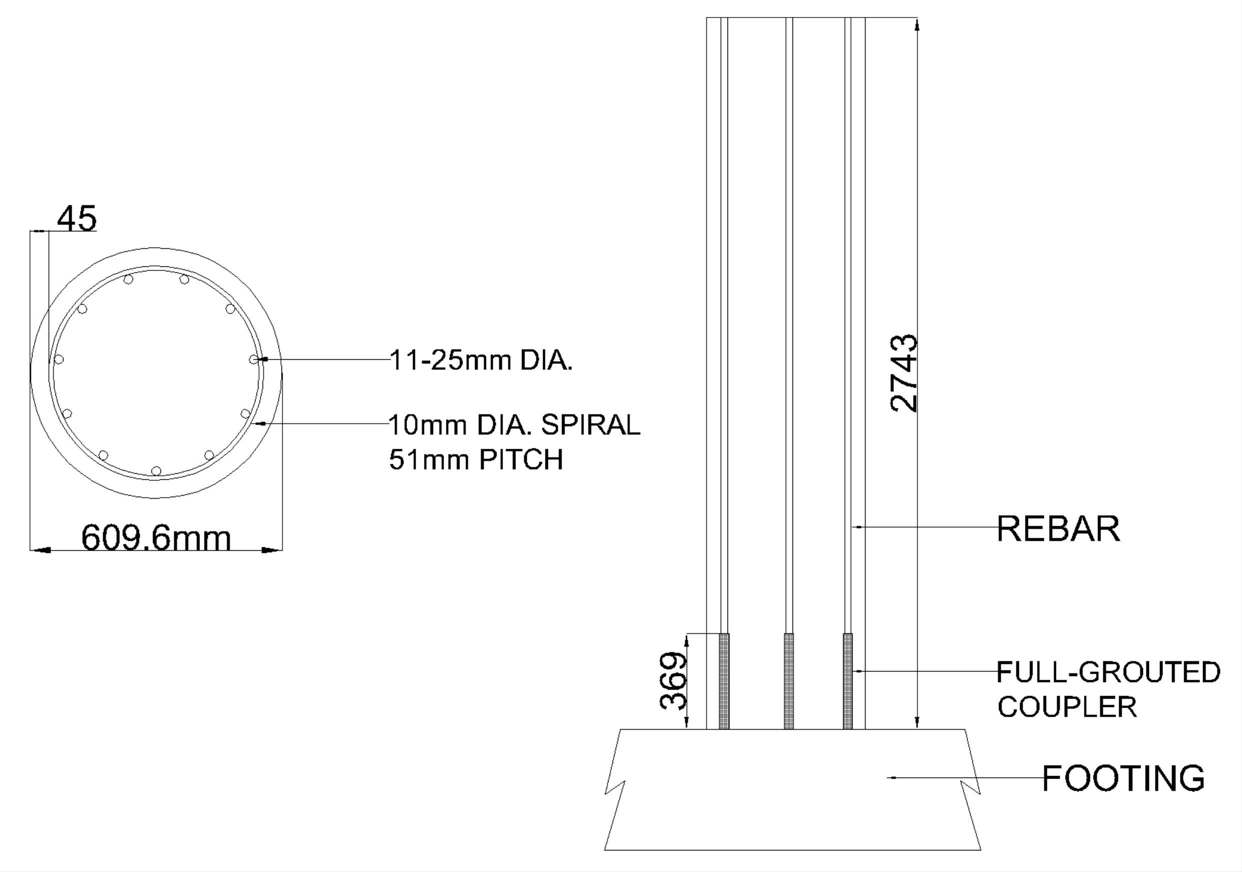


Figure 3. Experimental Column Dimension and Reinforcement

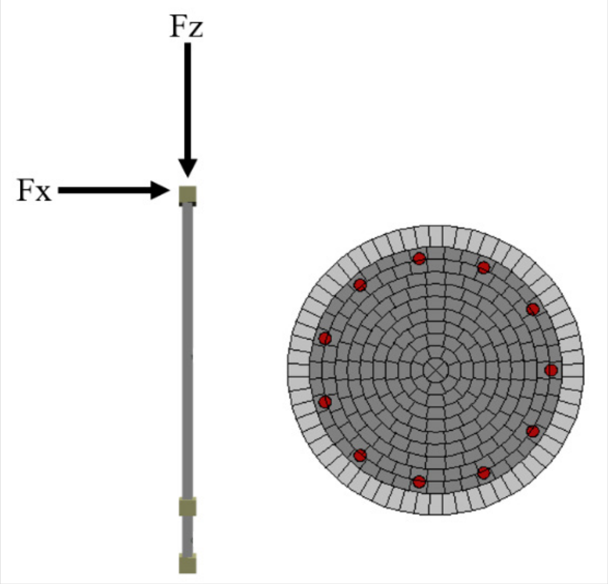


Figure 4. Model Configuration in Seismostruct

The column specimen is modeled according to its actual configurations, support, and loading conditions, as can be seen in Figure 4. It is fixed at the base and is subjected to a monotonic incremental lateral force at x-direction and a constant axial compressive force of 978 KN at the top. The load factor given to fully define the magnitude of the incremental load is defined using the response control phase, set with a target displacement value of 0.2m at the column top before the pushing action stops.

Force-displacement curve from the experiment is compared with the ones generated by Seismostruct. As can be observed in Figure 5, although the initial stiffness of the pushover curve from the analytical model is slightly higher compared to the experiment, the values for maximum lateral load and ultimate displacement are comparable with a difference of 5% and 3.5%, respectively. Nevertheless, since the results closely match, an interpretation is presumed that the modeling technique carried out in this verification model using Seismotruct can simulate the response of a real structure with a coupler. The researcher then adopted this approach and proceeded with the study.

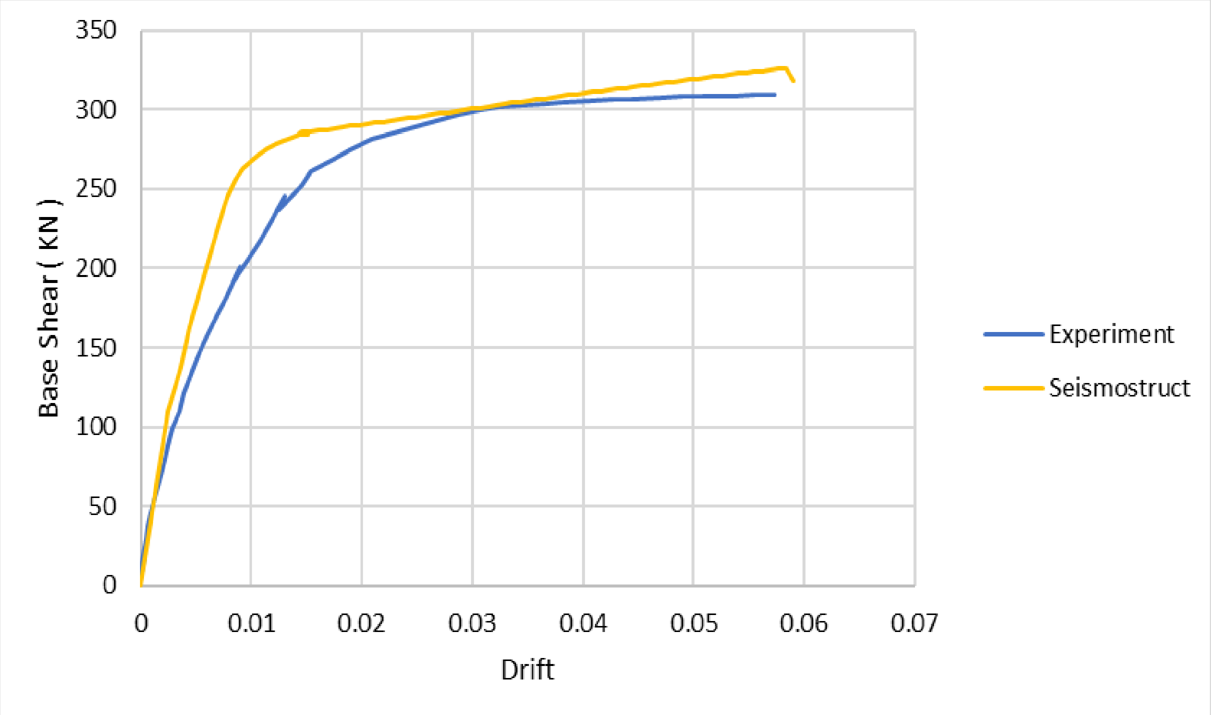


Figure 5. Force-displacement Response Comparison

2.3.2. Precast Beam-Column Connection Using Coupler Configuration

Different coupler locations are taken into consideration. For the first, second, and third arrangements, the distance of the couplers from the face of the beam-column joint varies. For the first configuration as shown in Figure 6A, the possibility of rebar connection using a coupler placed within the plastic hinge region is explored, specifically at the face of the joint. For the second and third schemes, the prescription of ACI was followed such that the location of Type 2 couplers must be beyond the distance 0.5D from the joint. Hence the second configuration has couplers placed directly 0.5D away from the joint face as described in Figure 6B. And the couplers for the third scheme are D away from the joint face, as shown in Figure 6C. For the last scheme as shown in Figure 6D, a hybrid of cast-in-place and precast has been explored. The lower half of the stories are made from cast-in-place concrete thereby not needing any couplers, and the upper half is made of emulative precast concrete connected by couplers located at the face of the joint. Cast-in-place concrete shall be placed on the joint and the coupler region within the beam region and grout within the precast column region.

2.3.3. Control Bar and Dextra Groutec S Specification

Dextra Groutec S Couplers are the specific brand of couplers used in this study. The control bars used in the experiment are Philippine rebars. Two control bar diameters are involved in this research: 25mm and 28mm diameter, to determine if the use of different diameters of Dextra Groutec couplers will have a significant impact on the overall performance of a structure. Tabulated below in Table 2 are the parameters used for the control bar and couplers, which are based on the experimental data carried out in Thailand by Dextra Company.

Table 2. Dextra Groutec Coupler Specifications

Parameter	Control Bar 25mm dia.	Dextra Groutec S25
Fy	462,700 kPa	475,000 kPa
Fu	602,000 kPa	623,000 kPa
εult	0.13	0.078
Esp	1,092,167 KN/m	1,960,999 KN/m
μ	0.0058	0.0104
Length		240 mm

Parameter	Control Bar 28mm dia.	Dextra Groutec S28
Fy	462,700 kPa	475,000 kPa
Fu	602,000 kPa	623,000 kPa
εult	0.13	0.078
Esp	1,092,167 KN/m	1,960,999 KN/m
μ	0.0058	0.0104
Length		240 mm

The post-yield stiffness is calculated using the equation,

$$E_{SP} = \frac{(f_{ult} - f_y)}{\epsilon_{ult} - f_y/E_s} \tag{1}$$

While the strain hardening ratio is obtained by dividing the post-yield stiffness by the initial elastic stiffness of the material (2).

$$\mu = \frac{E_{SP}}{E_s} \tag{2}$$

2.3.4. Description of Frame Structure and First Stage Analysis

A total of 30 models are conducted throughout this study which comprises 6 conventional structures (served as the benchmark for emulative performance); 6 structures for scheme 1, 6 structures for scheme 2, 6 structures for scheme 3, and 6 structures for scheme 4, all of which are summarized in Table 3 alongside its model name. Figure 6 shows the different types of coupler configurations used in this study. All of the structures have the same plan configuration: 3 bays with a meter distance each span and 3.2 meters floor-to-floor height.

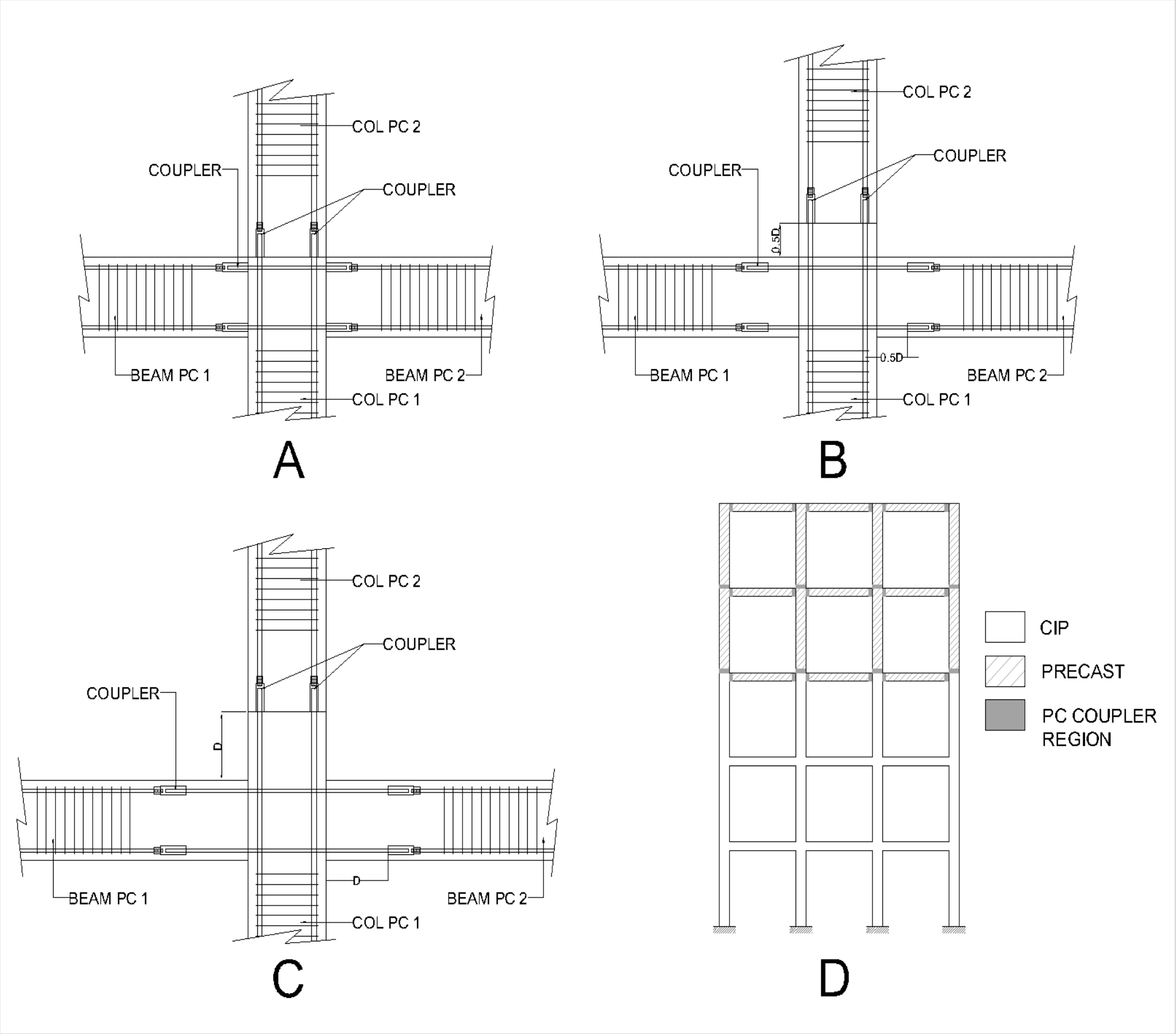


Figure 6. (A) Couplers Placed at the Face of the Joint (B) Couplers Placed Distance 0.5D Away From the Joint (C) Couplers Placed Distance D Away From the Joint (D) Hybrid Configuration

Table 3. Model Name Convention

Configuration	Two-Story		Five-Story		Ten-Story	
	Using 25mm dia.	Using 28mm dia.	Using 25mm dia.	Using 28mm dia.	Using 25mm dia.	Using 28mm dia.
Cast-in-Place	CIP_2F_25	CIP_2F_28	CIP_5F_25	CIP_5F_28	CIP_10F_25	CIP_10F_28
Coupler at Face	CoupFace_2F_S25	CoupFace_2F_S28	CoupFace_5F_S25	CoupFace_5F_S28	CoupFace_10F_S25	CoupFace_10F_S28
Coupler at 0.5D	Coup0.5D_2F_S25	Coup0.5D_2F_S28	Coup0.5D_5F_S25	Coup0.5D_5F_S28	Coup0.5D_10F_S25	Coup0.5D_10F_S28
Coupler at D	CoupD_2F_S25	CoupD_2F_S28	CoupD_5F_S25	CoupD_5F_S28	CoupD_10F_S25	CoupD_10F_S28
Hybrid	Hybrid_2F_S25	Hybrid_2F_S28	Hybrid_5F_S25	Hybrid_5F_S28	Hybrid_10F_S25	Hybrid_10F_S28

The initial structural design of the structures is carried out through a linear static analysis using response spectrum method in ETABS software. Material properties including 4000 PSI or 28 MPa for the specified compressive strength, A615 Grade 60 for longitudinal rebars, and A615 grade 60 for the ties and stirrups are used in the design. Two-dimensional models with fixed support at the foundation level are created with beams and columns reduced stiffness to 0.35 and 0.7, respectively. Mass source concentrated at the center mass of each story is applied automatically, defined with 100% load from the dead load. Iterative P-delta analysis based on load factor 1.2DL is performed to consider P-delta on an element-by-element basis and local buckling is captured effectively.

Once the structure's concrete and rebar specifications are established, the second stage of analysis, which is the pushover analysis, is performed. Beams and columns are modeled as nonlinear elements, which are idealized by employing a distributed plasticity model. The lateral load pattern used in the analysis is based on the first modal shape since the structure is symmetrical and the geometry has no complexity. Hence, uniform distribution loading pattern is adopted in doing the pushover analysis.

Almost the same process as that of the experimental verification model was done in all 30 models. Initially, nonlinear material properties are defined: mander's model for concrete and the menegotto-pinto model for the reinforcement bar and couplers.

Subsequently, cross-sections are defined in the "sections tab" wherein the section type (concrete rectangular), material, dimensions, and reinforcement are explicitly designated. The transverse reinforcement for the confined property of Mander's is considered in the Section Definition, by assigning the transverse reinforcement characteristic, hence calculating the confinement factor.

The element class used to define the nonlinear behavior of elements is the inelastic displacement-based distributed plasticity (infrmDB). Since it is necessary to model small segments for the coupler region, this type of approach is best suited for this study since an element in infrmDB is discretized into several segments to have mesh refinement and eventually achieve good accuracy in the case of higher-order distributions of deformations. This leads to improved convergence criteria and the overall stability of the analysis. For each section of all the elements, it is discretized into 300 fiber sections, wherein one fiber is allotted for each rebar, and the remaining fibers for the concrete part.

30 two-dimensional models are configured based on different scenarios as previously discussed. Modeling of nodes and line elements differs depending on the model scheme, where the distance of coupler from the face of the joint and the length of coupler varies. A typical beam-column joint modelling is shown in Figure 7. Short line elements such as the element from the center to the face, distance away from the face, and the coupler elements are not further discretized, as infrmDB already acknowledges these as short elements and good convergence criteria can already be achieved.

In the series of analyses, the applied loadings consist of incremental and permanent loadings. The permanent gravity load in the z-direction includes the self-weight of the elements while the incremental load (pseudo-static load) for the push action that is applied in the y-direction is a force-based type of loading strategy. Force-based incremental loading instead of displacement-based type is employed in this study since pushing a structure up until its predefined shape may conceal its true response characteristics.

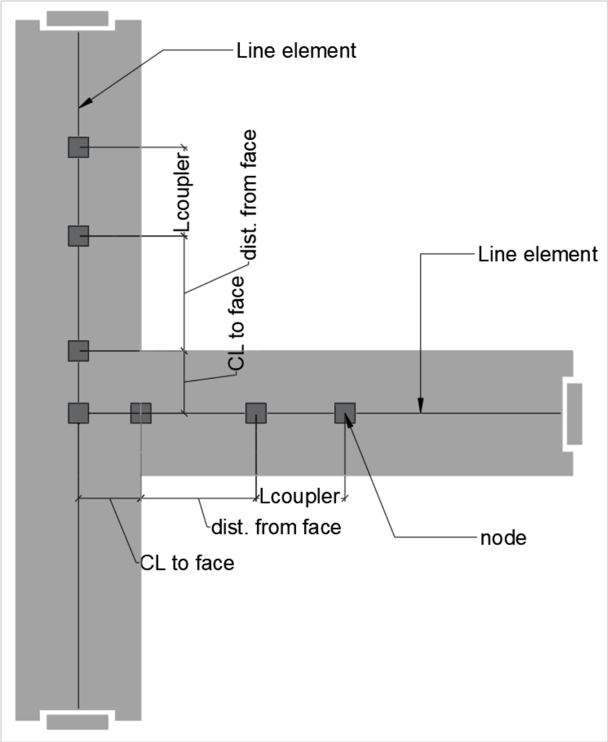


Figure 7. Beam-Column Joint Modelling

The magnitude of incremental load P_i at a particular analysis step is specified as the product of P_0 which is the nominal value assigned in incremental loading type and the load factor λi at "i step" (3).

$$P_i = \lambda i\ P_0 \tag{3}$$

In this study, a Response Control Phase is the solution scheme utilized to solve for the load factor at any given step. As the name implies, the response of a particular node is controlled by the algorithm in the structure. The load factor is automatically solved by the program such that the load vector Pi at increment "i" corresponds to the displacement of the controlled node at that step. The researcher set the controlled node at the top of the structure/roof, its target displacement at which the analysis is set to be terminated, and the number of increments before the analysis end. 100 pushover analysis steps are assigned in all models instead of the typical 50 steps to produce more refined pushover curves and avoid convergence problems.

Lastly, to effectively identify the instances at which different performance states are reached, defining the damage criteria by assigning threshold values of strain, fracture, yielding, and cracking of concrete is carried out. Material strain is used as the parameter to define the different performance criteria.

Values are assigned based on the maximum value the material can handle. Crushing of concrete core would signify that concrete strains at core already exceeded the ultimate crushing strain of confined concrete, which is -0.006. Spalling or the crushing of concrete outside of the core takes place if a value of -0.002 is exceeded. Yielding and fracture of rebar and coupler occur once the yield strain and fracture strain, respectively, are exceeded. Table 4 shows the criteria set by the researcher.

Table 4. Performance Criteria Limit in Seismostruct

Damage Criteria	Material Strain
Spalling of Concrete	-0.002
Crushing of Core Concrete	-0.006
Yielding of Steel	0.00246
Fracture of Steel	0.13
Yielding of Coupler S25	0.00253
Fracture of Coupler S25	0.078
Yielding of Coupler S28	0.00233
Fracture of Coupler S28	0.068

Once all the models are analyzed, the pushover curves are obtained from the post-processing tab of Seismostruct and plotted using Excel. Ultimate displacement, ductility, and energy dissipation of all the structures are calculated. The displacement once the elements of the structure experience crushing of the core, is taken as the ultimate displacement. This can also be seen on a pushover graph as the displacement before the sudden drop of the pushover curve. For the displacement ductility, the ratio of yield displacement and ultimate displacement is obtained. Yield displacement for the curve is determined by tracing the intersection of the drawn slope from (0,0) passing through the 66% percentile (2/3 Fmax) and the horizontal line passing through 5/6 Fmax, where Fmax is the maximum force on the graph. Finally, the energy dissipation of the structures is determined by calculating the area under the capacity curve. To simplify the calculations, the trapezoidal rule is adopted (4).

$$\sum_{k=1}^{n} \frac{f(x_{k-1})}{2} \Delta x_k \qquad (4)$$

3. Results and Discussion

The result of the pushover curves of the 30 models, created with different story heights and configuration of coupler locations is discussed herein.

3.1. Location of Couplers

3.1.1. Two-Story Structure Using 25 mm Dia. Rebar

Figure 8 shows the pushover curve of five different models for a two-story structure, one of which is the control model (CIP Structure) and the remaining four are the structures modeled with different locations of couplers from the face of the beam-column connection. It can be seen that Hybrid_2F_S25 emulates the shape of the CIP_2F_S25's curve but has a smaller ultimate displacement, with a difference of only 3.63%. CoupFace_2F_S25 and Coup0.5D_2F_S25, as expected produced curves that have shorter ultimate displacement compared to CIP with a difference of 34.59% and 25.87%, respectively. CoupD_2F_S25 also exhibited good performance in emulating the curve of CIP, but with much greater ultimate displacement difference of 11.63% and lower maximum force attained.

As summarized in Table 5, displacement ductility for the structures with couplers is significantly smaller compared to the CIP's, except for Hybrid_2F_S25 and CoupD_2F_S25. The same result can be seen when it comes to energy dissipated, with CoupD_2F_S25 a little bit lower compared to Hybrid_2F_S25 because of its lower maximum force overall.

Table 5. Results for Two Story Structure (S25) in Displacement Ductility and Energy Dissipation

Type	Displacement Ductility	Energy Dissipated, KN-m
CIP_2F_25	8.87	169.50
CouplerFace_2F_S25	5.87	106.37
Coupler0.5D_2F_S25	6.85	118.14
CouplerD_2F_S25	8.29	147.47
Hybrid_2F_S25	8.37	162.70

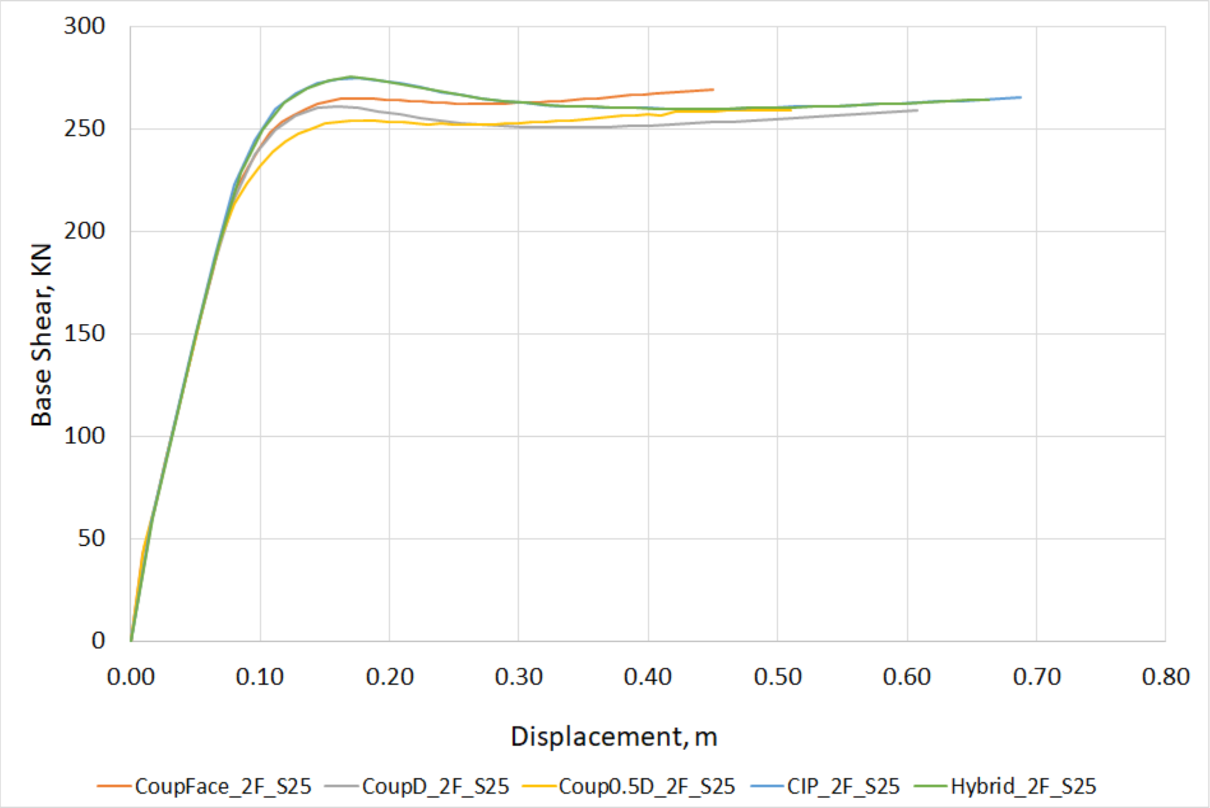


Figure 8. Pushover Curve of Two Story (S25)

3.1.2. Two-Story Structure Using 28 mm Dia. Rebar

Table 6. Results for Two Story Structure (S28) in Displacement Ductility and Energy Dissipation

Type	Displacement Ductility	Energy Dissipated, KN-m
CIP_2F_28	8.62	203.22
CouplerFace_2F_S28	4.88	107.93
Coupler0.5D_2F_S28	5.71	122.74
CouplerD_2F_S28	7.64	166.23
Hybrid_2F_S28	8.09	189.92

The same behavior is demonstrated by the two-story structures with 28mm dia. rebar and Groutec S28 coupler, compared to the two-story structures with 25mm dia rebar and coupler, as can be seen in Figure 9. Hybrid_2F_S28 exhibited the most plausible performance of emulating the CIP global performance in terms of ultimate displacement, ductility, and energy dissipation, with a difference of 6.12% for the ultimate displacement compared to the CIP. This is then followed by CoupD_2F_S28 with a yield displacement difference of 13.99% compared to CIP_2F_28. Both CoupFace_2F_S28 and Coup0.5D_2F_S28 reached only half of what CIP_2F_28 can in terms of top displacement, with a significant difference of 43.15% and 34.69%, respectively. Energy Dissipation and displacement ductility among the 4 models also have similar results with the two-story structures with S25, as can be seen in Table 6.

3.1.3. Five-Story Structure Using 25 mm Dia. Rebar

Table 7. Results for Five-Story Structure (S25) in Displacement Ductility and Energy Dissipation

Type	Displacement Ductility	Energy Dissipated, KN-m
CIP_5F_25	5.11	507.24
CouplerFace_5F_S25	3.46	285.64
Coupler0.5D_5F_S25	3.88	324.26
CouplerD_5F_S25	4.05	367.57
Hybrid_5F_S25	4.79	429.65

CIP_5F_25 model is compared with the four models with coupler and can be seen in Figure 10 that all four models have lower Fmax and ultimate displacement, which eventually yielded lower energy dissipation. In terms of ultimate displacement, Hybrid_5F_S25 outperformed the three coupler models having a difference of 8.54% compared to that of the CIP. It is then followed by CoupD_5F_S25,Coup0.5D_5F_S25,and CoupFace_5F_S25 with ultimate displacement differences of 20.33%, 26.96%, and 34.96% , respectively.

In terms of displacement ductility, CoupD_5F_S25 and Hybrid_5F_S25 have close values to CIP_5F_25. This is quite different when it comes to energy dissipation, where it is evident that Hybrid_5F_S25 has the closest value to CIP, as shown in Table 7.

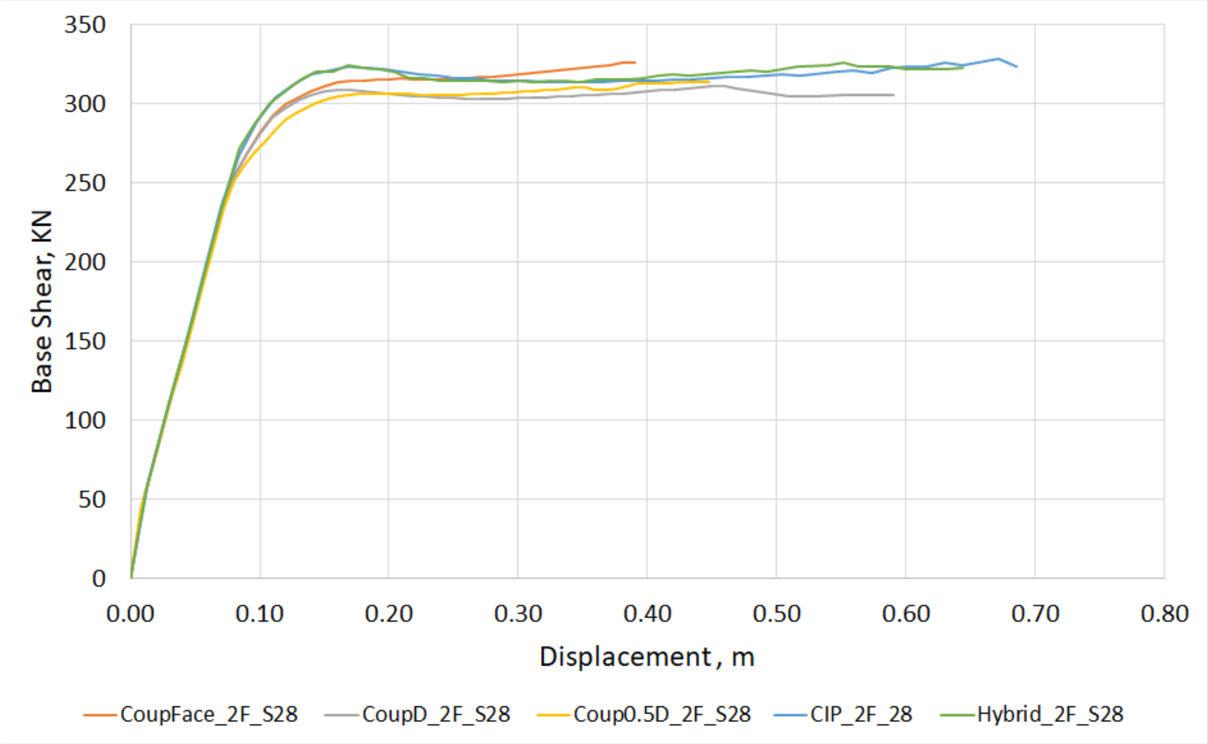


Figure 9. Pushover Curve of Two Story (S28)

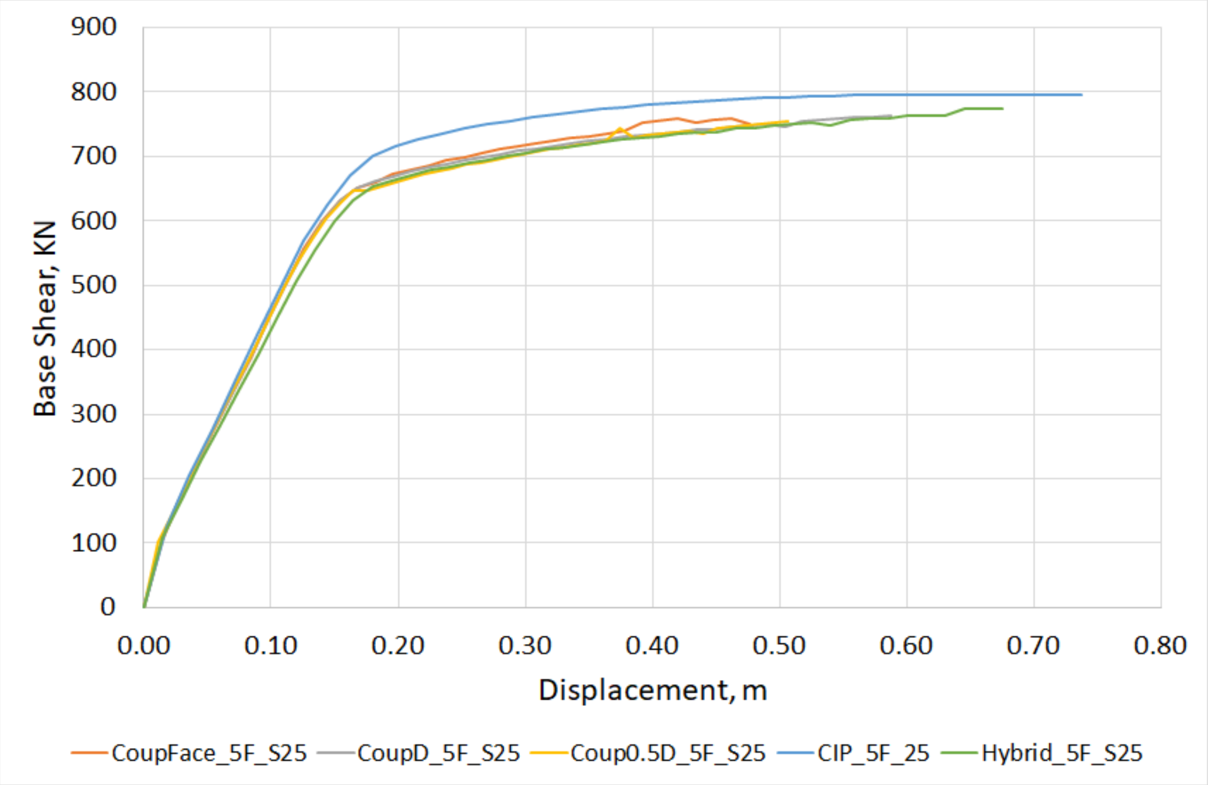


Figure 10. Pushover Curve of Five Story (S25)

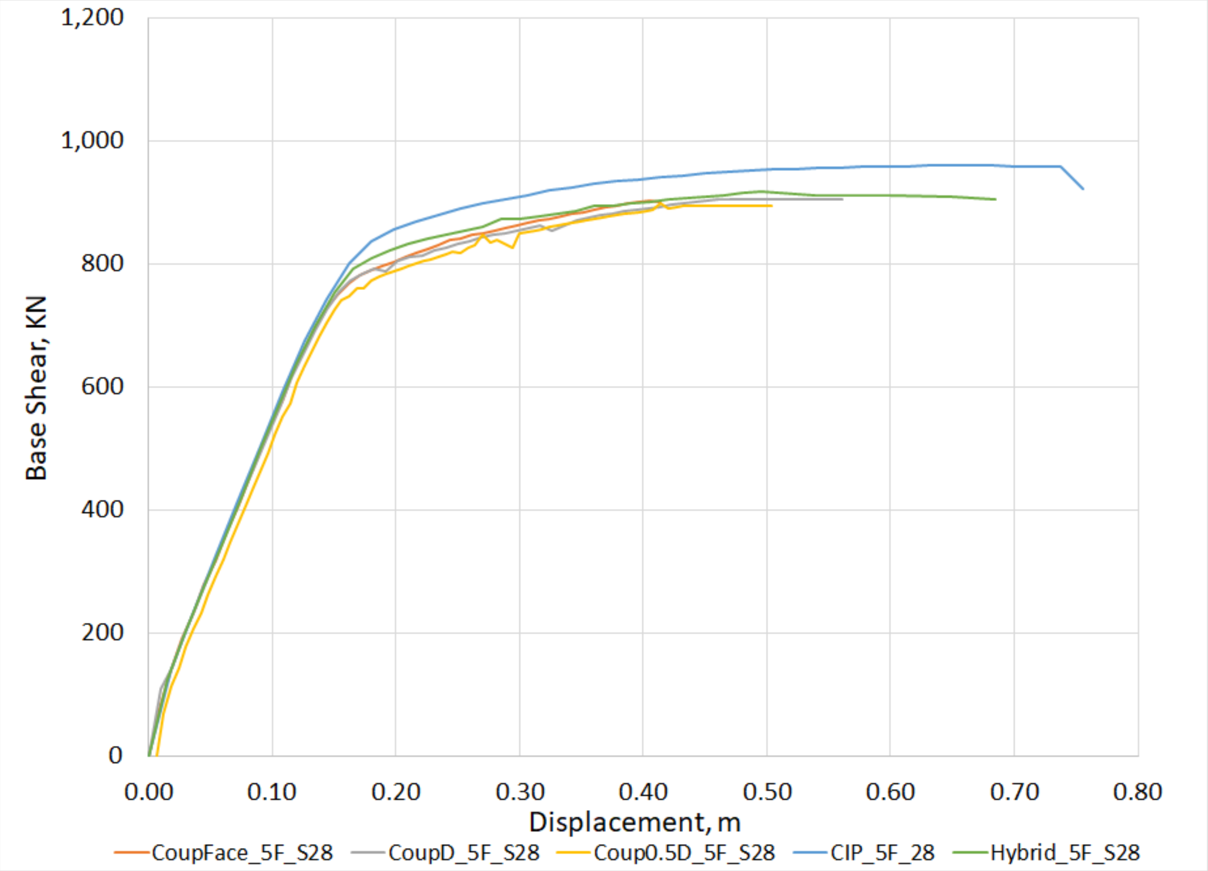


Figure 11. Pushover Curve of Five Story (S28)

3.1.4. Five-Story Structure Using 28 mm dia. Rebar

Table 8. Results for Five-Story Structure (S28) in Displacement Ductility and Energy Dissipation

Type	Displacement Ductility	Energy Dissipated, KN-m
CIP_5F_28	5.15	624.90
CouplerFace_5F_S28	2.97	285.86
Coupler0.5D_5F_S28	3.63	363.10
CouplerD_5F_S28	3.98	416.53
Hybrid_5F_S28	4.85	535.35

The comparative analysis for the five-story structure using 25mm dia. rebar and S25 coupler is quite the same as for the five-story structure using 28mm dia. rebar and S28 coupler, although the percentage differences between the CIP and the models with coupler is bigger than the previous models for five-story. For instance, Hybrid_5F_S28 garnered the lowest percentage difference in terms of ultimate displacement, which is 9.39%, followed by CoupD_5F_S28,Coup0.5D_5F_S28,and CoupFace_5F_S28 having percentage differences of 25.81%, 33.33%, and 45.77% respectively. It is evident that the pattern may be the same compared to five-story models using 25mm dia. but the percentage differences are much higher.

The values of ductility and energy dissipation for the four models in comparison with the CIP model are also as expected, that is Hybrid_5F_S28 has the closest values among the other variable models, as shown in Table 8.

3.1.5. Ten-Story Structure Using 25 mm dia. Rebar

The pushover curve comparison of the ten-story structures is comparable to the results of five-story structures, wherein hybrid_10F_S25 produced the most emulative curve to CIP in terms of ultimate displacement, with a percentage difference of 10.56%. Figure 12 shows that the CIP model inhibits the largest Fmax and the remaining four models are a little bit lower but still comparable. This, and the significant differences in the ultimate displacement lead to reduced values of displacement ductility and energy dissipation. Nevertheless, Hybrid_10F_S25 model produces the best performing curve among the other models with coupler based on ultimate displacement, ductility, and energy dissipation as shown in Table 9.

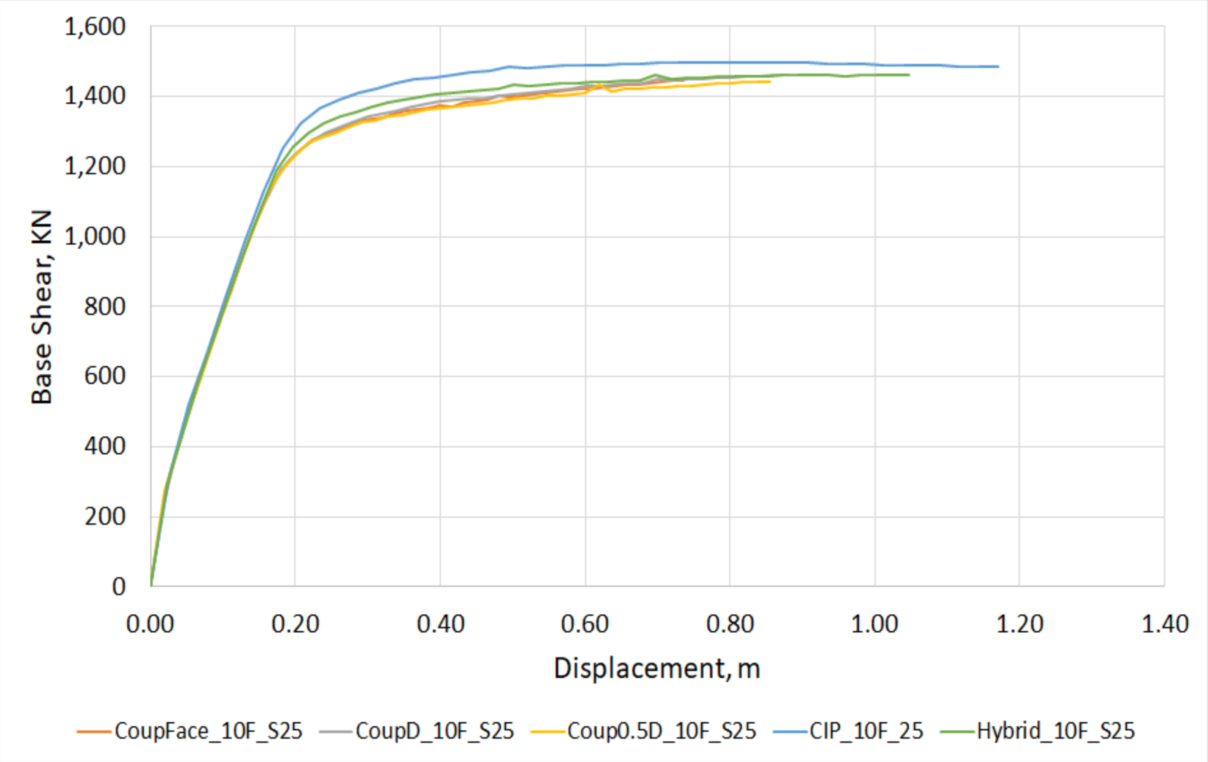


Figure 12. Pushover Curve of Ten-Story (S25)

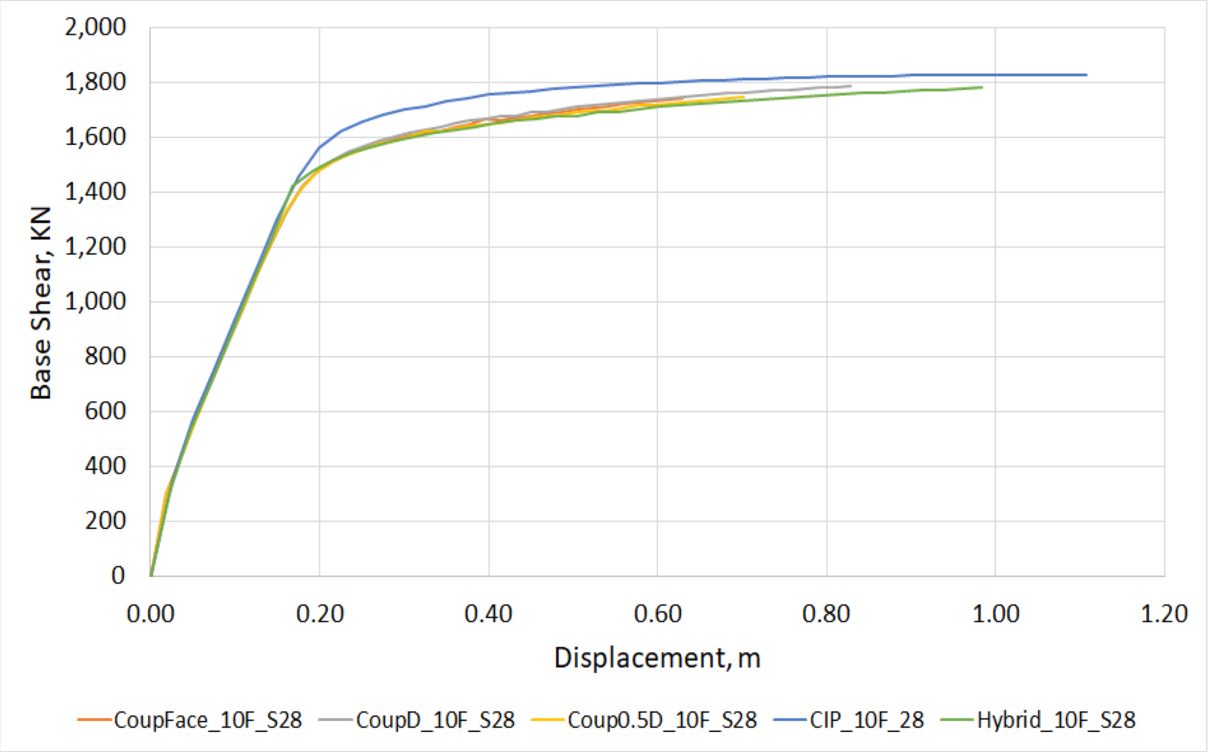


Figure 13. Pushover Curve of Ten-Story (S28)

Table 9. Results for Ten-Story Structure (S25) in Displacement Ductility and Energy Dissipation

Type	Displacement Ductility	Energy Dissipated, KN-m
CIP_10F_25	7.08	1582.78
CouplerFace_10F_S25	4.57	889.87
Coupler0.5D_10F_S25	5.25	1057.85
CouplerD_10F_S25	5.32	1102.80
Hybrid_10F_S25	6.31	1357.92

Table 10. Results for Ten-Story Structure (S28) in Displacement Ductility and Energy Dissipation

Type	**Displacement Ductility**	**Energy Dissipated, KN-m**
CIP_10F_28	6.43	1798.93
CouplerFace_10F_S28	3.75	886.95
Coupler0.5D_10F_S28	4.20	1008.27
CouplerD_10F_S28	4.79	1239.63
Hybrid_10F_S28	5.77	1502.71

3.1.6. Ten-Story Structure Using 28 mm dia. Rebar

The ten-story model with 28mm dia. rebar and S28 Groutec couplers shows expected results as with the previously discussed models as can be seen in Figure 13. Hybrid_10F_S28 produced a curve will a smaller ultimate displacement compared to CIP_10F_28, with a percentage difference of 11.26%. This can be easily compared with Hybrid_10F_S25 which has a smaller percentage difference of 10.56%. The remaining models with coupler have much lower values of ultimate displacement with percentage differences of 25.32% for CoupD_10F_S28, 36.69% for Coup0.5D_10F_S28, and 43.18% for CoupFace_10F_S28.

The same observation can be seen in the performance of the models with couplers in terms of displacement ductility and energy dissipation, that of which the hybrid_10F_S28 produced the closest values to those of the CIP_10F_S28, as demonstrated in Table 10.

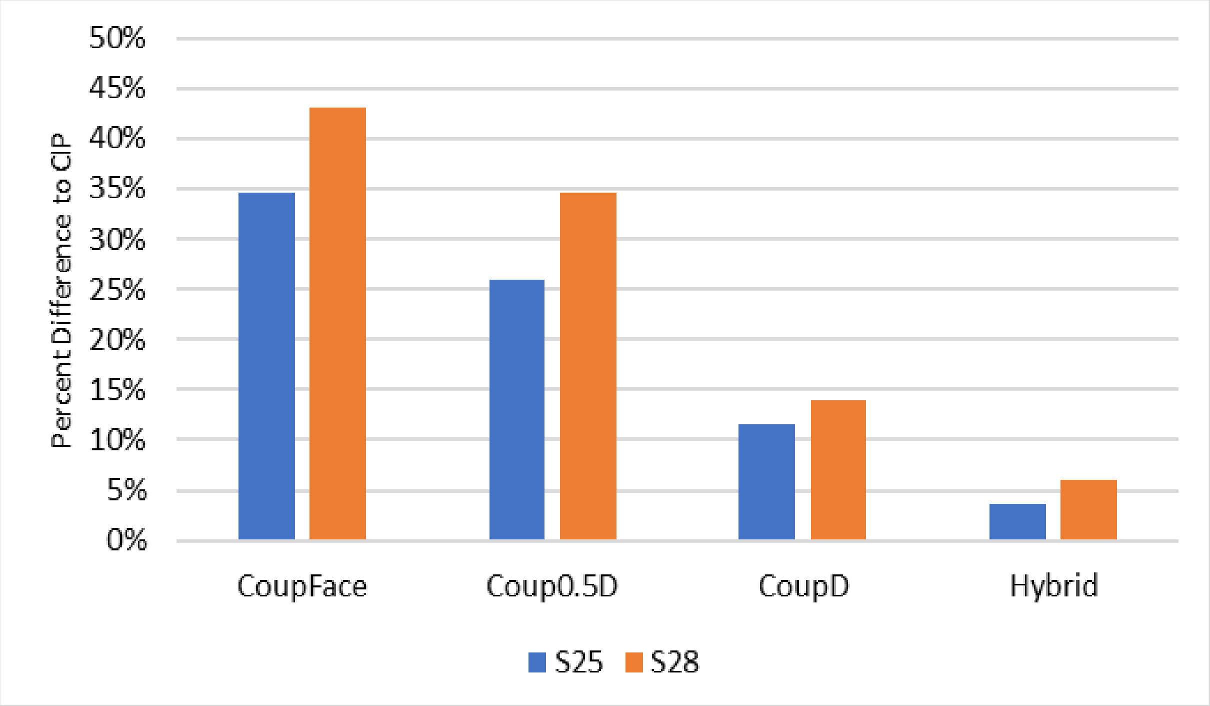
Applying the acceptance criterion for emulative precast elements in terms of displacement ductility by Tazaarf, the hybrid configuration is more than 90% of the ductility of CIP for all the models of varying story height, hence is accepted as an emulative pc structure.

3.2. Dextra Groutec S25 vs S28

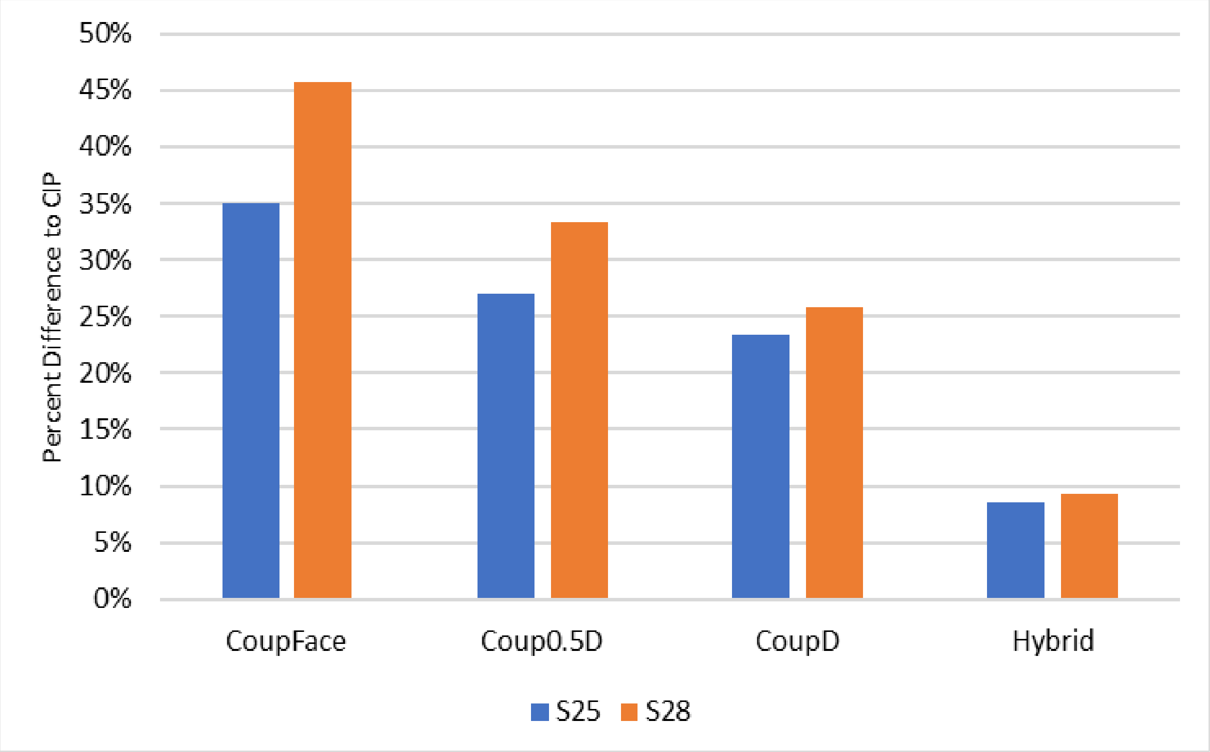
The performance comparison between models using Dextra Groutec S25 and S28 is also carried out. By the use of the percent differences of the models with couplers to the CIP, the two coupler diameters are compared side by side through a series of bar charts below.

As can be seen in Figures 14 - 16 it can be observed that for the three performance criteria, the models that used Dextra Groutec S28 yielded higher percentage differences from the CIP models in comparison with the models that used Dextra Groutec S25. In the matter of assessing the ultimate displacement, there is a significant difference between S25 and S28 for the couplers modeled at the face and the couplers modeled 0.5D away from the face. While the couplers placed D away from the face and the hybrid models show a minimal difference between the two types of couplers.

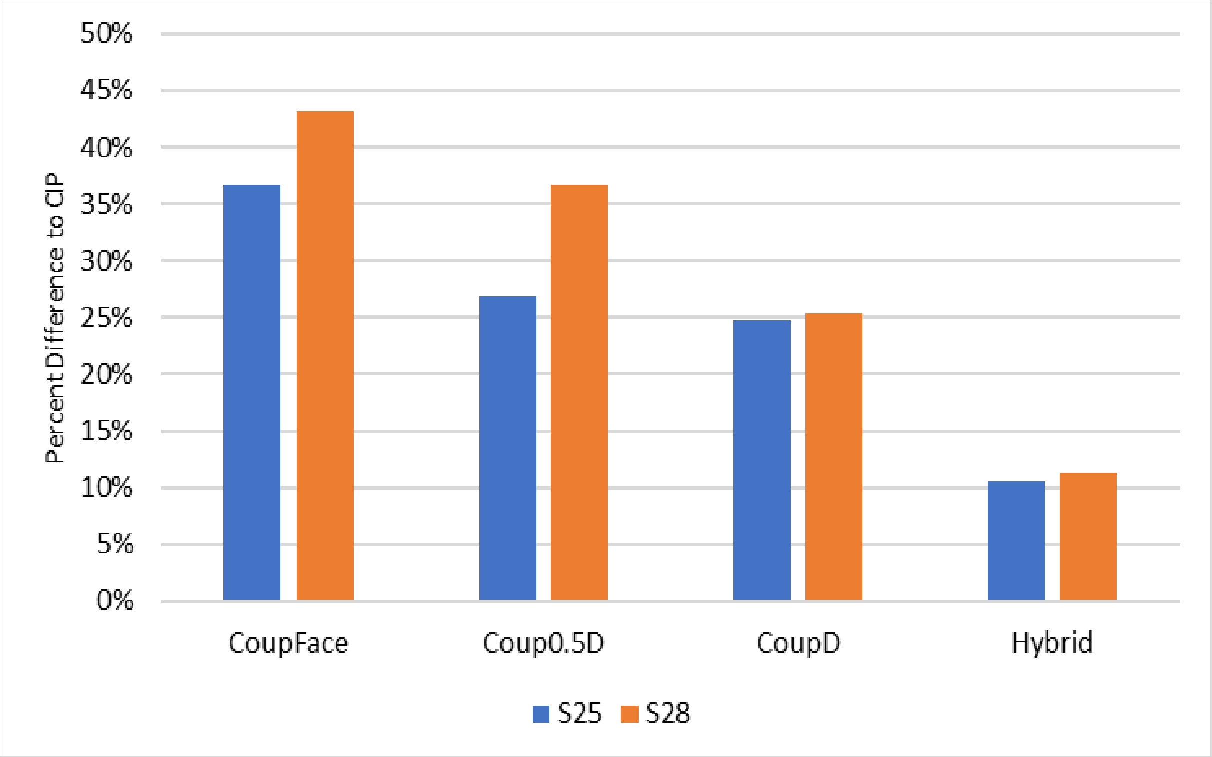
In terms of displacement ductility and energy dissipation, the three coupler location schemes: CoupFace, Coup0.5D, and CoupD show that models using Groutec S28 incurred a higher percent difference from CIP than S25. Hybrid models on the other hand indicate that no considerable percentage difference can be seen between the two types of couplers.


Percent Difference to CIP
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
CoupFace
Coup0.5D
CoupD
Hybrid
S25
S28

A

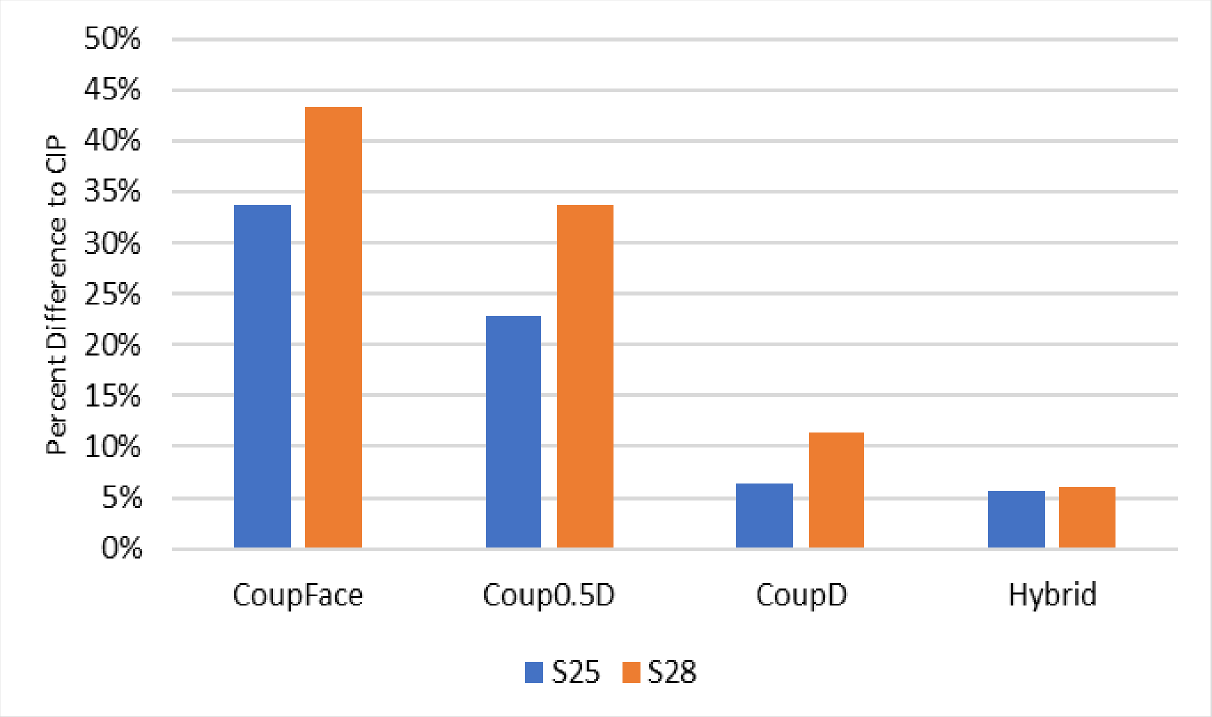

Percent Difference to CIP
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
CoupFace
Coup0.5D
CoupD
Hybrid
S25
S28

B

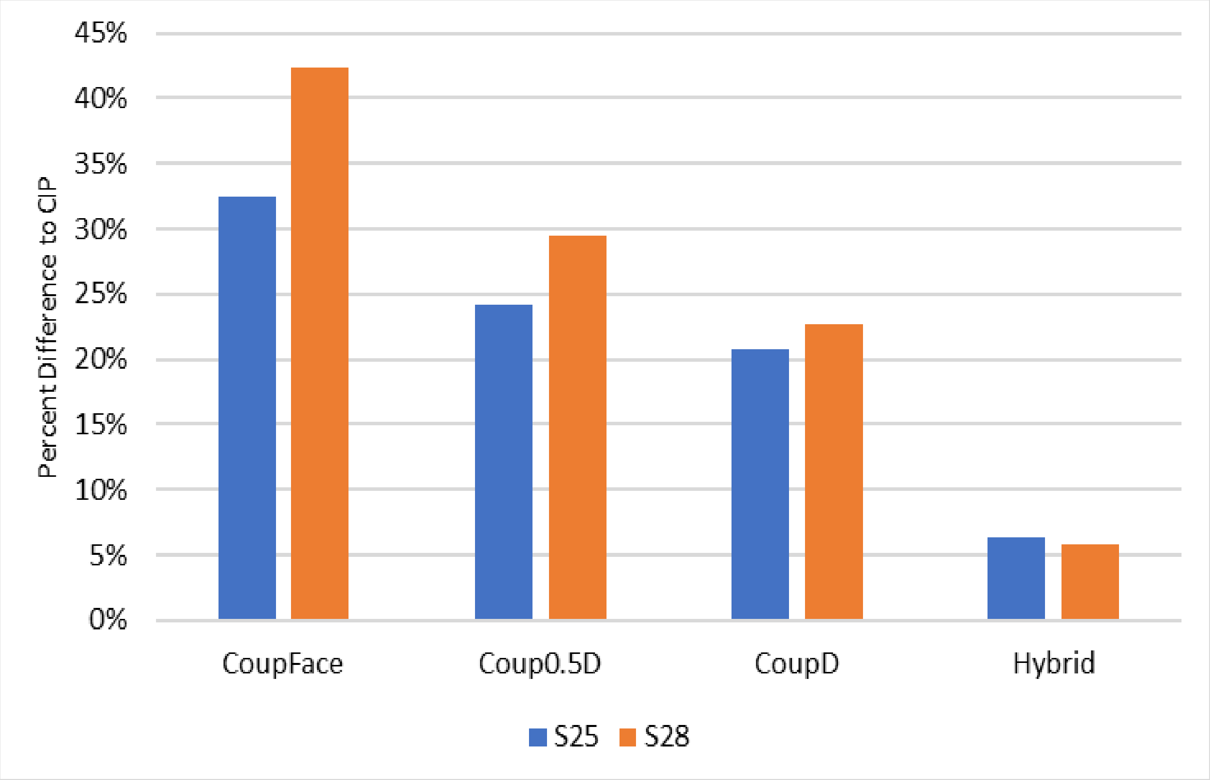


C

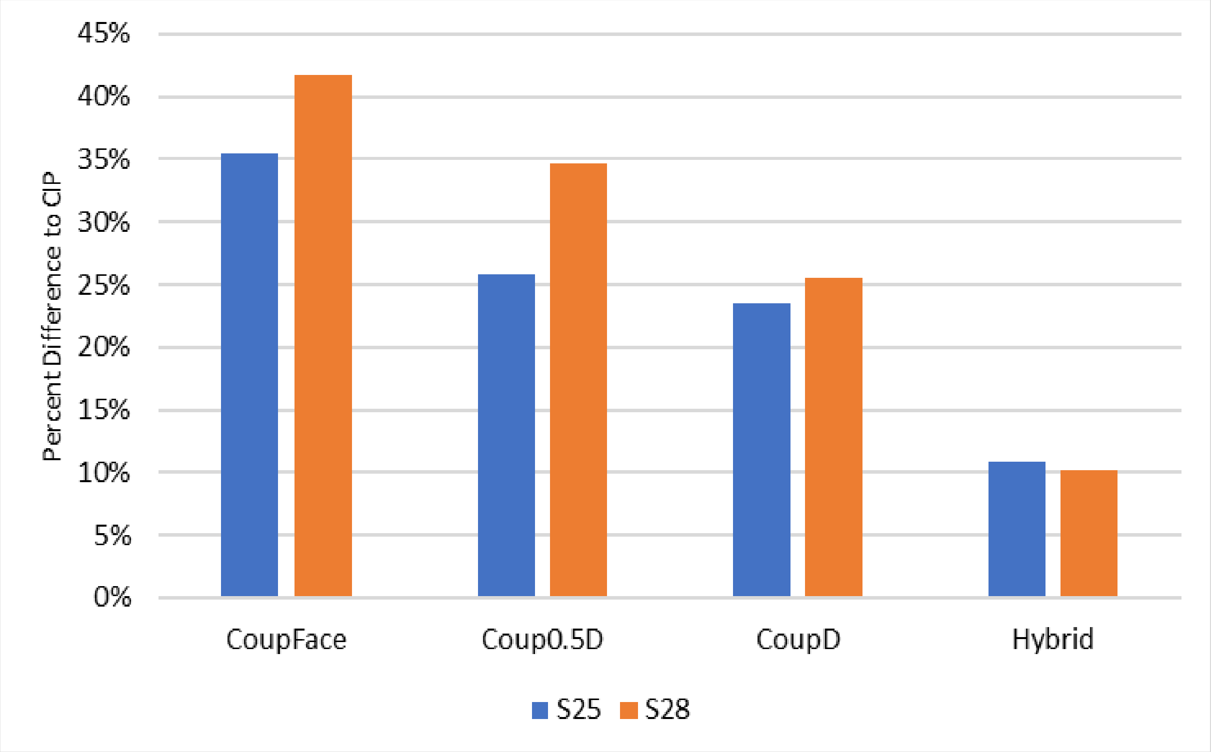
Figure 14. Percentage Difference to CIP In Terms of Ultimate Displacement (A) Two-Story (B) Five-Story (C) Ten-Story



A

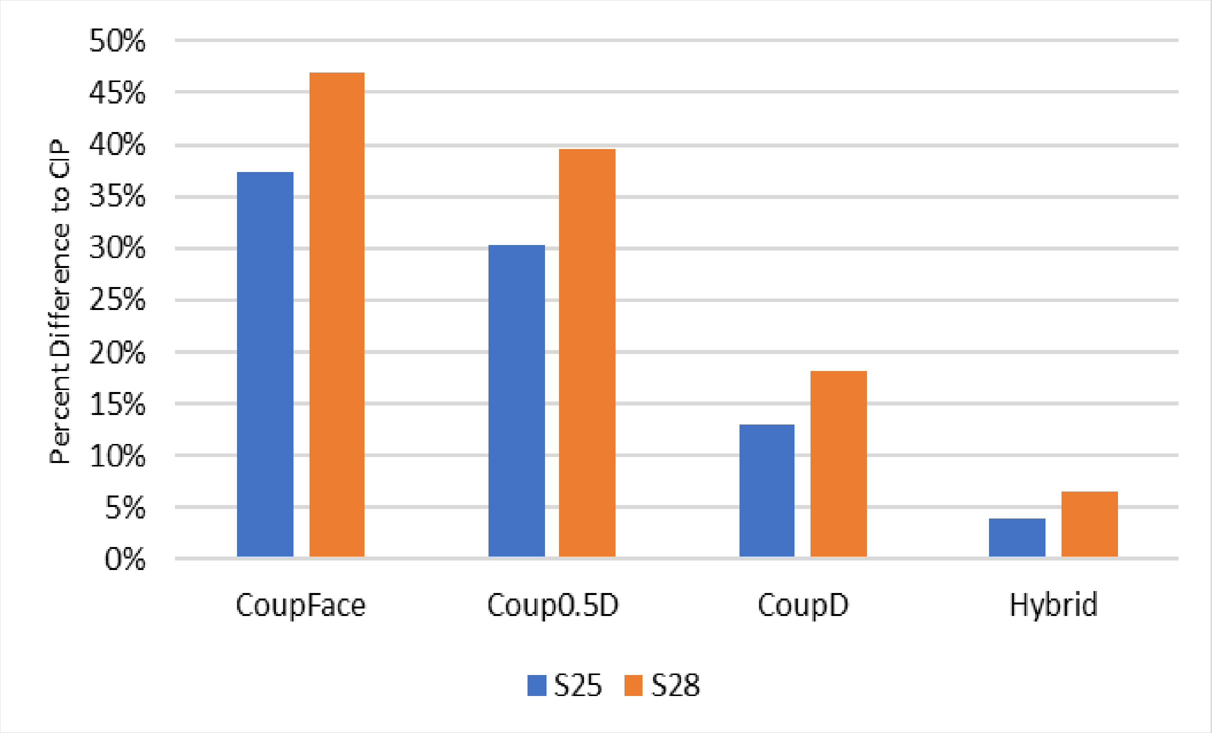


B

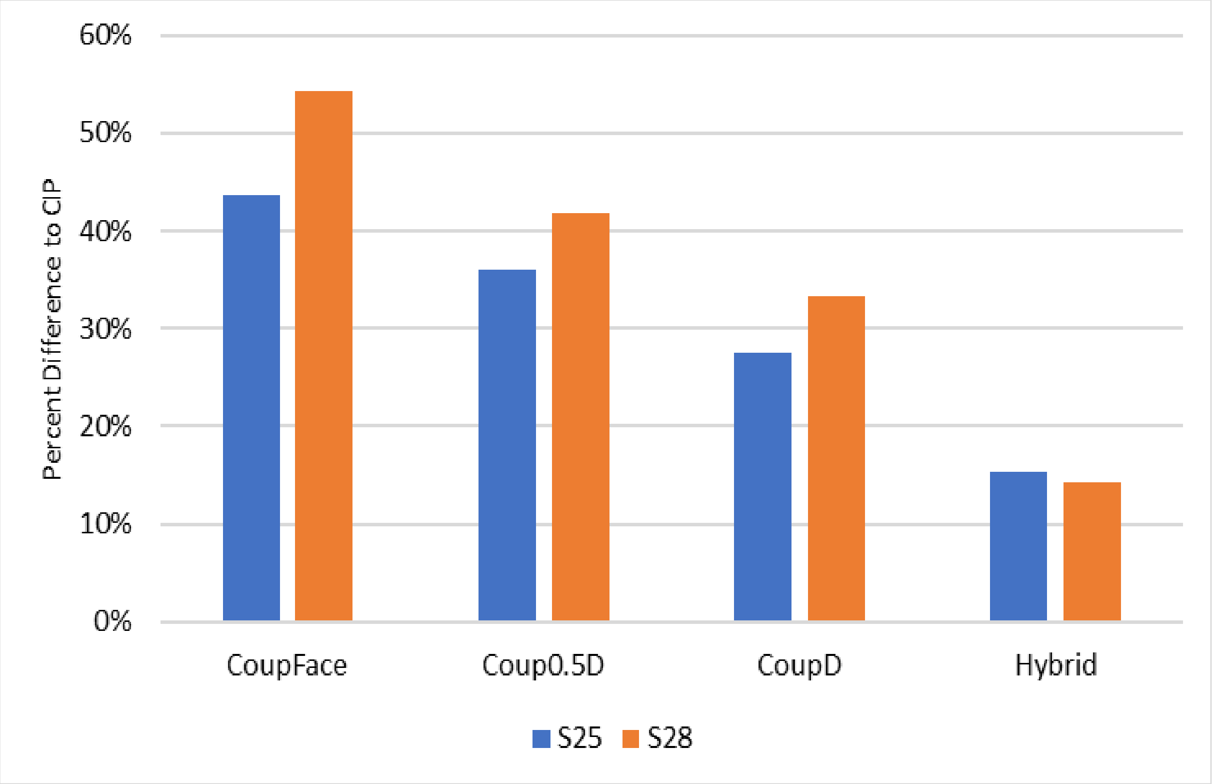


C

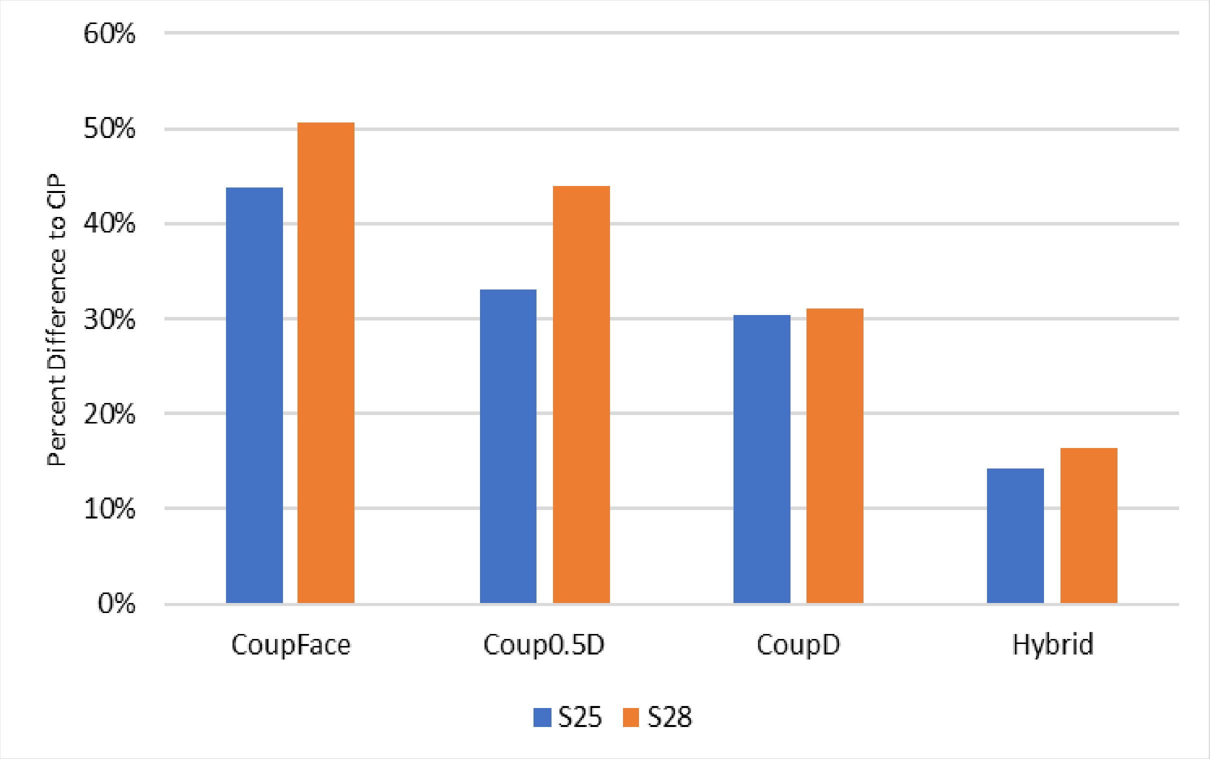
Figure 15. Percentage Difference to CIP In Terms of Ductility (A) Two-Story (B) Five-Story (C) Ten-Story


Percent Difference to CIP
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
CoupFace
Coup0.5D
CoupD
Hybrid
S25
S28

A

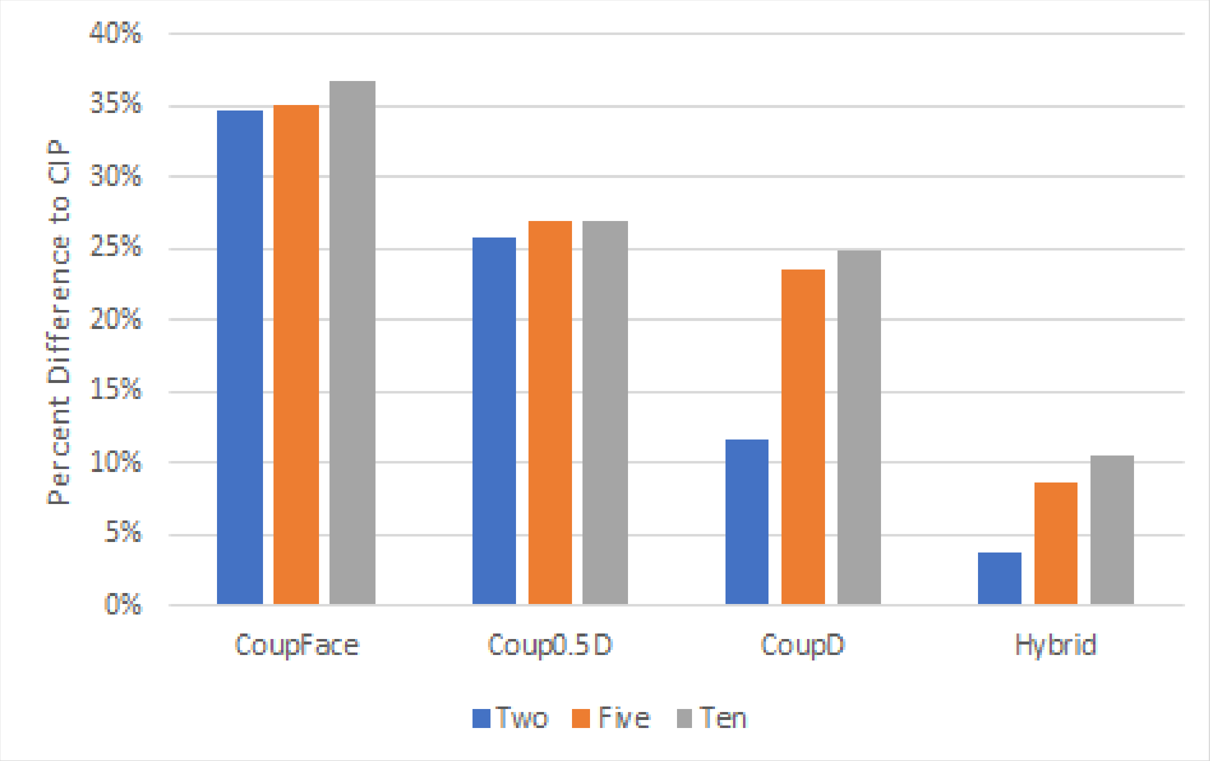

Percent Difference to CIP
60%
50%
40%
30%
20%
10%
0%
CoupFace
Coup0.5D
CoupD
Hybrid
S25
S28

B

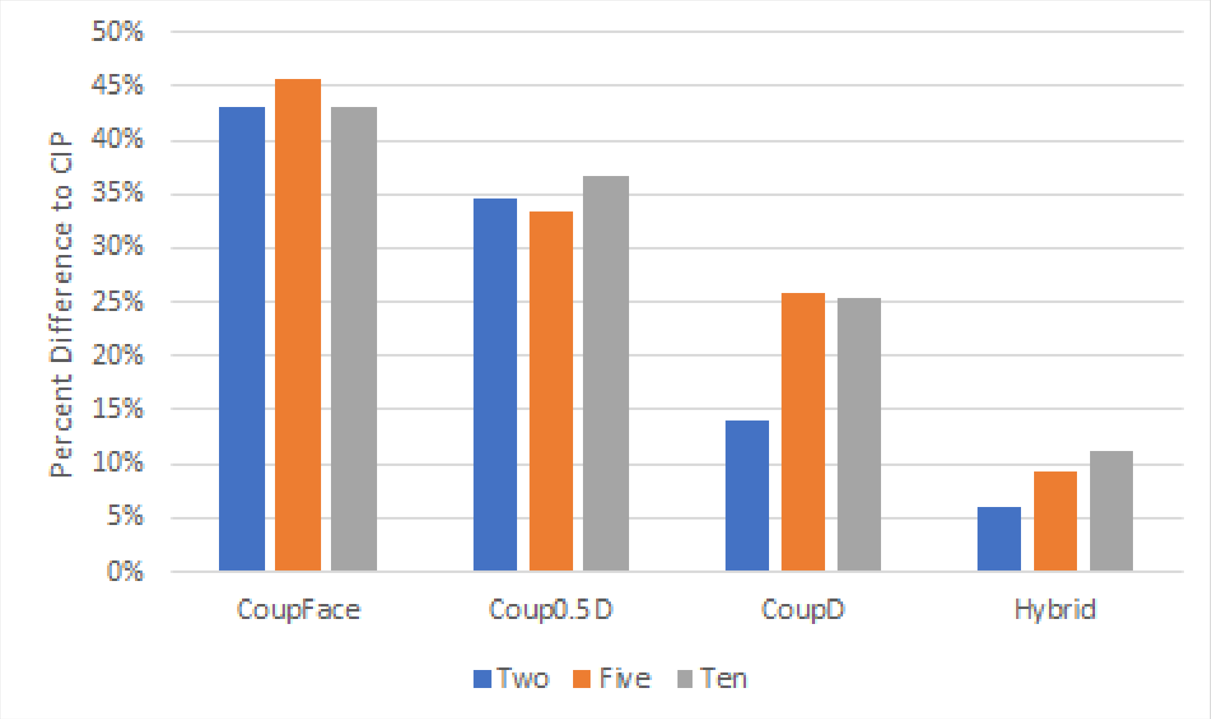


C

Figure 16. Percentage Difference to CIP In Terms of Energy Dissipation (A) Two-Story (B) Five-Story (C) Ten-Story

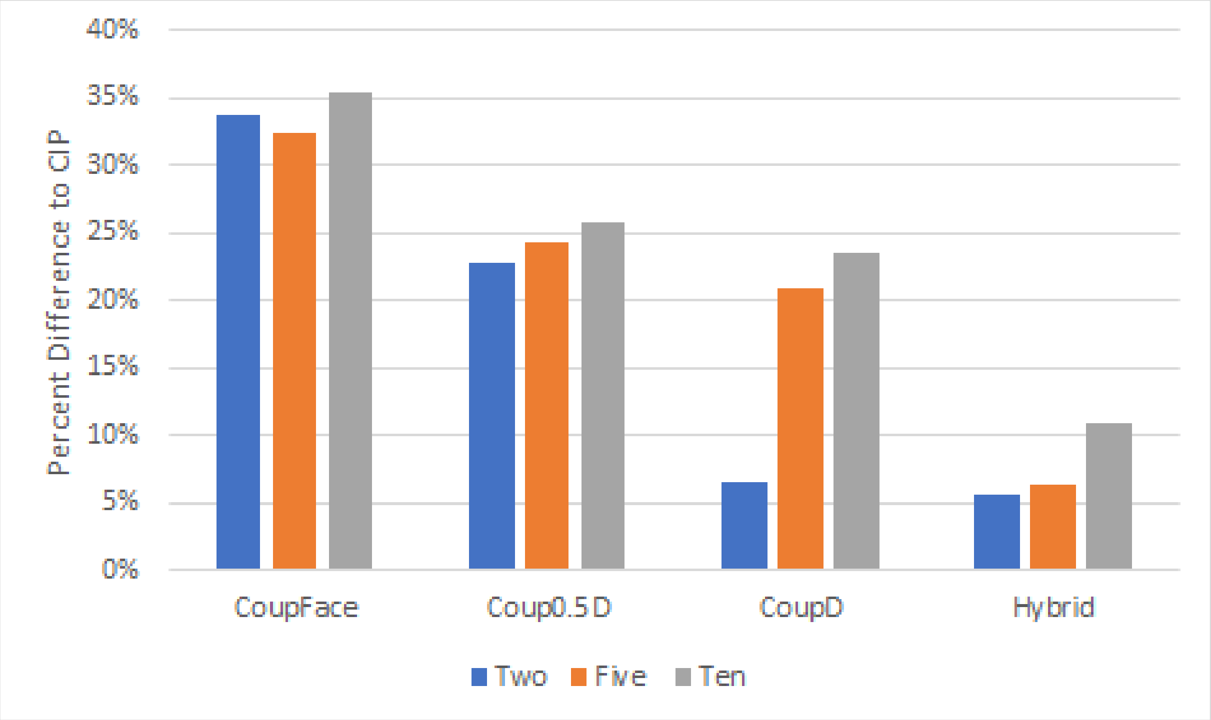


A

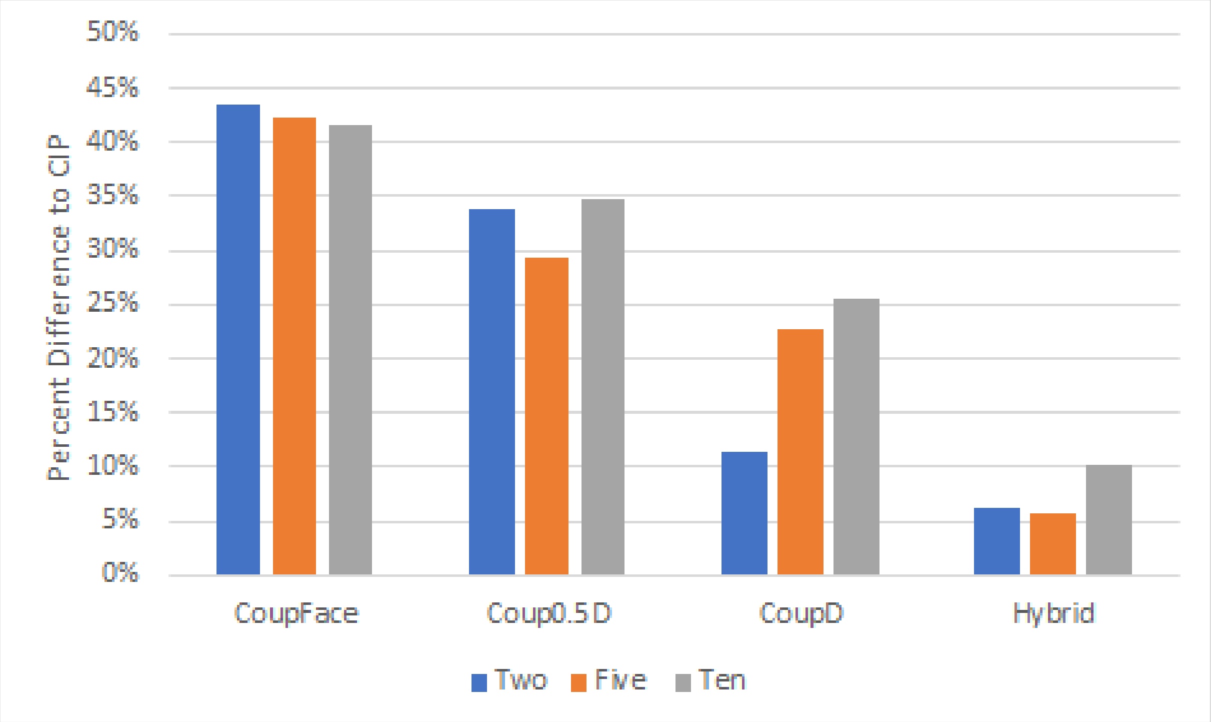


B

Figure 17. Percentage Difference to CIP In Terms of Ultimate Displacement for Different Story Height (A) S-25 (B) S-28

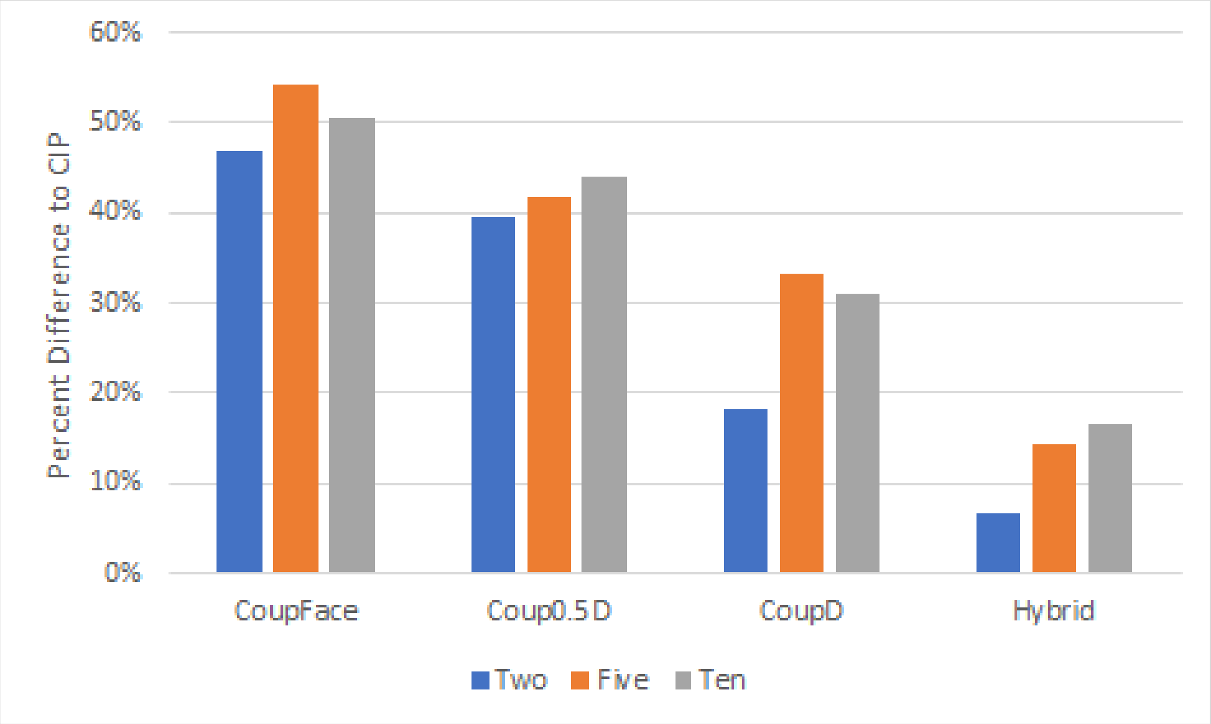


A



B

Figure 18. Percentage Difference to CIP In Terms of Ductility for Different Story Height (A) S-25 (B) S-28



A

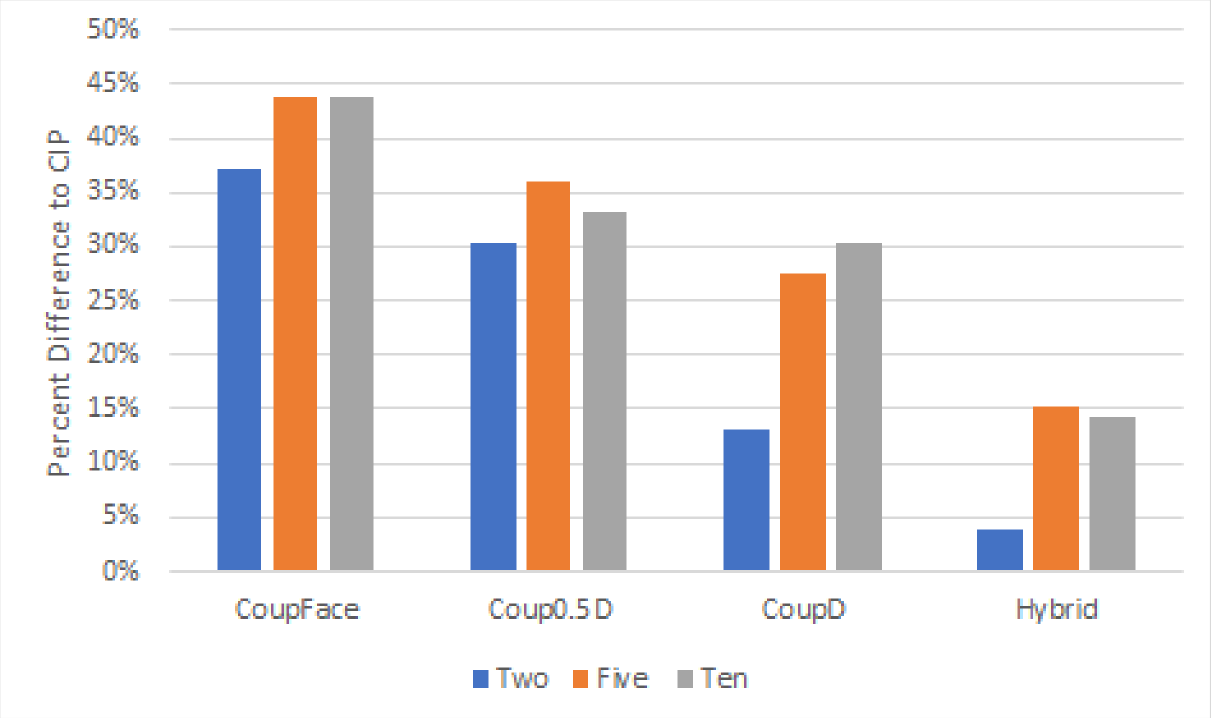


Figure 19. Percentage Difference to CIP In Terms of Energy Dissipation for Different Story Heights (A) S-25 (B) S-28

3.3. Story Height

The effects of Groutec couplers and how it affects the emulative behavior of precast based on building height are also taken into account. Percent differences from CIP models of the two, five, and ten-story structure models with couplers based on the three global performance criteria are compared, as shown in Figures 17- 19.

Based on the figures, almost the same percentage difference occurs for all the structures with different story heights if the couplers are placed at the face and 0.5D away from the face of the beam-column joints. However, different results can be seen for the structures where couplers are located D away from the support and the hybrid scheme. Data show that the two-story frames produced a lower percentage difference to CIP compared to the five and ten-story building frames.

3.4. Effects of Coupler on Structures

Finally, to determine whether using couplers instead of continuous reinforcement rebars in vertical structures has a significant influence on their global performance, statistical evidence by the use of paired t-test is carried out by the researcher. T-value taken from the statistics table is 2.571. Results in Table 11 indicate that there are significant differences in the values of the global ultimate displacement, ductility, and energy dissipation of structures if the couplers are placed either directly after the face, 0.5D/D away from the face, or in a hybrid configuration. An exception can be seen under the hybrid scheme in terms of energy dissipation which shows that there is no significant difference between the values of energy dissipated by the conventional cast-in-place structure and the hybrid configuration.

Table 11. Paired T-test Results

Configuration	T-value	Verdict
Ultimate Displacement		
Coupler at Face	8.67	s.d.
Coupler at 0.5D	7.71	s.d.
Coupler at D	5.13	s.d.
Hybrid	4.43	s.d.
Displacement Ductility		
Coupler at Face	9.06	s.d.
Coupler at 0.5D	8.17	s.d.
Coupler at D	6.63	s.d.
Hybrid	6.81	s.d.
Energy Dissipation		
Coupler at Face	2.77	s.d.
Coupler at 0.5D	2.68	s.d.
Coupler at D	2.59	s.d.
Hybrid	2.46	n.s.d.

**s.d. – significant difference*

n.s.d. – no significant difference

4. Conclusion

Ultimate displacement, displacement ductility, and energy dissipation at the structural system level are critical factors to consider in earthquake resiliency. Sufficient ductility shall be designed within the hinge regions to accommodate lateral deformations without sudden failure. Hence, the role of the couplers including their location and classification plays an important factor to determine whether a considerable amount of ductility and dissipated energy is reduced in reference to the conventional cast-in-place structure, due to their role as end-to-end connectors in precast element structures.

An experiment where a large-scale specimen precast column connected by grouted couplers is used as the reference to carry out a verification study and determine the appropriate modeling techniques. Seismostruct is found to be a reliable finite element software that can simulate the force-deformation of the experimental column with couplers. Inelastic displacement-based distributed plasticity frame element with 300 fiber sections is used to model the elements to produce finer mesh and refined accuracy, especially for short elements like the coupler region.

For the comparative analysis of structures with different story heights and different coupler configurations, the validated software Seismostruct is used, applying the necessary parameters and modeling techniques to produce reasonable pushover curves.

The effect of the location of Dextra Groutec Couplers is found to reduce the capacity in terms of the emulative response of the precast structure to that of the CIP based on the three performance criteria: ultimate displacement, displacement ductility, and energy dissipation. Pushover curves for all the structures with different coupler configurations produced almost the same pattern of behavior that is hybrid configuration generated the most similar curve to that of the CIP model. This is deemed accurate considering the bottom half of the story, which is subjected to larger demand forces due to fixity at the base is cast-in-place, while the remaining upper story, composed of precast elements with couplers placed at the face of the joints moves along the movement of the lower half, hence lesser demand forces and eventually, yielding and plastic hinge mechanism is experienced. Differences in terms of ultimate displacement range from 3%-10%, while ductility is 6%-10%, and for energy dissipation is 4%-16% for the hybrid configuration, which can be considered emulative. Moreover, the hybrid configuration passed the acceptance criterion for emulative PC structure set by Tazaarf since the displacement ductility of these models all exceeded the 0.9μcip criterion.

It is then followed by the models where Dextra couplers are placed at a distance D away from the support. Based on the results of the models' global performance, it is evident that it is still far from emulating the behavior of CIP models although the restriction of the ACI code indicates that the use of Type 2 couplers is allowed outside of the 0.5D region from the face of the joint.

The two critical coupler configurations, which are the models that have Dextra Coupler 0.5D away from the face of the joint and directly after the face of the joint performed poorly in terms of emulating the global behavior of the CIP models. This is quite anticipated since placing these mechanical devices within the plastic hinge zone that has lesser strain capacity compared to the spliced rebar will reduce the overall buildings' performance in terms of ductility and dissipated energy. Although differences range from 35%-46% for Dextra couplers at the face and 25%-35% for the couplers located 0.5D away from the face, placing the couplers in such locations is still feasible as long as the reduced displacement capacity is still higher than the displacement demand of a structure.

Longer Dextra Groutec Couplers such as the S28 reduce the ultimate displacement, ductility, and dissipated energy of CIP structures more in comparison to S25, S28 demonstrating a 3-10% percent difference to CIP compared to S25. Long couplers, due to higher rigid length factor undergo reduced ultimate strain compared to a shorter coupler. This circumstance, along with increased stiffness of the reinforced concrete frame reduces the displacement capacity of structures.

The height of the structure is not a strong factor in the emulative response of the RC precast frame for the models with couplers placed in the critical region such as at the face and 0.5D away. However, the difference in performance for shorter story heights such as two-story structures is deemed to perform better compared to taller structures for the models with couplers D away from the joint and the hybrid configuration.

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REFERENCES

[1] M. Singh, J. Mehta, K. Soni, "Study on Comparison of Precast and Cast In-Situ Construction of the Structure based on Social Category", International Research Journal of Engineering and Technology, Vol. 06, No. 06, pp. 2065-2068, 2019.

[2] Y. Kurama, S. Sritharan, R. Fleischman, J. Restrepo, R. Henry, N. Cleland, S.K. Ghosh, P. Bonelli,

"Seismic-Resistant Precast Concrete Structures: State of the Art", Journal of Structural Engineering, Vol. 144, No.4, 2018. DOI: 10.1061/(ASCE)ST.1943-541X.0001972

[3] ACI-ASCE Committee 550, "Guide to Emulating Cast-in-Place Detailing for Seismic Design of Precast Concrete

[4] S. Patel, "Benefits of Rebar Couplers", Satish Patel, https://satishpatel.net/benefits-of-rebar-couplers/ (accessed May 19, 2022).

[5] ACI Committee 439, "Types of Mechanical Splices for Reinforcing Bars (ACI 439.3R-07)", ACI Manual of Concrete Practice, 2007.

[6] M. Ameli, J. Parks, D. Brown, C. Pantelides, "Seismic Evaluation of Grouted Splice Sleeve Connections for Reinforced Precast Concrete Column–to–Cap Beam Joints in Accelerated Bridge Construction", Vol. 60, No. 2, pp. 80-103, 2015. DOI: 10.15554/pcij.03012015.80.103

[7] Z. Haber, M. Saiidi, D. Sanders, "Seismic Performance of Precast Columns with Mechanically Spliced Column-Footing Connections", ACI Structural Journal, Vol. 111, No. 3, pp. 639-650, 2014. DOI: 10.14359/51686624

[8] Z. Haber, M. Saiidi, D. Sanders, "Behavior and Simplified Modeling of Mechanical Reinforcing Bar Splices", ACI Structural Journal, Vol. 112, No. 2, 2015. DOI: 10.14359/51687455

[9] M. Tazarf, M S. Saiidii, "Design And Construction Of Bridge Columns Incorporating Mechanical Bar Splices In Plastic Hinge Zones", Center for Civil Engineering Earthquake Research, 2015.