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# Numerical study on the flexural rigidity of prefabricated lightweight concrete beam-column joints

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**ABSTRACT**

In this numerical study, the rigid behavior of prefabricated beam-column joints has been investigated. Due to the criticality of lateral loads in seismic zones, the ductility, strength, and energy absorption of prefabricated rigid joints are crucial. Lightweight concrete is a common material in prefabricated concrete structures because of its advantages, such as easy formwork and transportation, as well as quick execution. Therefore, this study investigates the effect of lightweight concrete on the flexural rigidity of prefabricated beam-column joints. Furthermore, this study evaluates other significant factors in prefabricated structures, including the integrity of the concrete-rebar connection and preventing rebar slippage. In this study, Abaqus software was employed to model lightweight concrete constructed from Leca (Light Expanded Clay Aggregate) and low strength grout. The present numerical study analyzes eight numerical models with the same geometry, but different materials and joints. In this set of models, two of them are without couplers, and the rest are pinned with couplers in a beam-column joint. This study concludes that the effect of lightweight concrete on the joint is negligible. Additionally, grout significantly affects the joint zone. By variation in the strength of grout in the joint zone, the ductility and strength of the structure are directly affected.

***Keywords:*** Prefabricated concrete, Lightweight concrete, Beam-column joint, Cyclic load, Joint zone grout

## Introduction

Prefabrication leads to higher quality of structural elements, more practicality, and efficiency in time and cost. During the recent earthquakes, some prefabricated buildings were damaged because of inadequate considerations for joint design. Although numerous experimental and analytical studies have been conducted on the performance of integrated beam-column joints under inelastic cyclic loads, the main problem is associated with energy dissipation capacity and low strength in prefabricated joints. Prefabricated concrete structures do not typically behave as ductile structures. A concentration of inelastic strains in the joint zone causes these structures to exhibit more unstable inelastic behavior than buildings constructed in situ. Recently, structural lightweight concrete has gained popularity. This material provides many advantages, including a reduction in concrete shrinkage, higher durability, easy formwork, faster execution, fire resistance, adequate soundproofing, and low permeability. Additionally, lightweight concrete provides a lower concrete density, which significantly reduces the dead load of the structure. As a result of this reduction, elements with a smaller cross-sectional area can be used. Due to its special technology and use of materials such as metal fibers, lightweight concrete is considerably more energy-absorbing compared to conventional concrete. A lightweight concrete is defined as concrete with a unit weight of less than 1840 (kg/m3), while a conventional concrete (heavy concrete) has a unit weight greater than 2400 (kg/m3). The lighter weight of the building also contributes to its cost efficiency. It results in a reduction in using structural materials such as girders and heavy concrete in the structure. A low heat transfer coefficient leads to fewer facilities and less energy consumption in the building. As a consequence of their dense and porous texture, they are generally suitable for tasks such



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as sawing, nailing, and grooving. In the present study, the variables of the numerical modelling are concrete type (lightweight concrete constructed from Leca and conventional concrete), joint zone with and without couplers, couplers length in pinned models, and grout type in the joint zone (low strength grout and conventional grout). Many types of research have been conducted on prefabricated beam-column joints but attention to the importance of utilizing light weight concrete beam-column joints was missed. Haber studied five half-scale bridge column models subjected to slow cyclic loading. Their study aimed to develop four new moment connections at column-footing joints in high seismic regions to reduce bridge construction time. Mechanical splices (an upset headed coupler and a grout-filled sleeve coupler) used in the connections of precast columns were connected to bars in cast-in-place footing. The seismic performance of the new connections was similar to that of conventional cast-in-place specimens. Clementi et al. studied the application of dowel pin connection in a concrete frame industrial building using nonlinear numerical analysis. Wu et al. conducted experiments on a precast concrete connection, and demonstrated the degradation velocity of the bearing capacity of the precast connection was higher than that of the cast-in-place connection [1-3] .Bahrami et al. tested a precast connection consisting of a continuous column and two corbels connected to beams. The corbels were connected to the bottom of beams in connection zone using screws or welding. Results of the studies demonstrated that the connection response including the strength, ductility, stiffness, and energy dissipation can reach approximately 80% of the monolithically casted connections. Xiao et al. introduced a dowel pin connection and recycled concrete that provided suitable seismic performance. Nzabonimpa et al focused on the finite element modeling of end plate connectors in precast concrete joints. Girgin et al. studied the seismic behavior of precast moment resisting frames with semi dry connection, consisting of column corbels, grouted parts and steel plates. The result of several dynamic analysis demonstrated that the response modification factors were less than the suggested value by the code provisions [4-6]. Fathi et al. proposed a type of metal connection using welded metal plates and gussets in order to provide connection integrity between precast continuous RC column and semi-precast RC beams. Based on the numerical and experimental results, this connection showed a performance similar to that of the monolithic connection. Guan et al. utilized high trength reinforcement bars in precast connections to reduce the congestion at the connection. Yan et al. provided precast connections with openings for the passage of bars in precast continuous beam members. The couplers were used to connect the bars of the beams and columns. The failure mode and plastic hinge formation of this connection depended on the slippage of bars, type of grout, array of the openings, and the couplers arrangement. Bompa and Elghazouli tested numerous specimens with different types of and their results showed that using PTCs (parallel thread couplers) provides more efficient connections for structural elements rather than other methods [7-10].

Ozturan et al. studied five different types of precast concrete frame connections, including one cast-in-place connection, two precast wet connections (at the end of beam and column) and two precast dry connections (welded and bolted with brackets). According to the results, the bolted connection provided maximum strength, ductility and energy dissipation rates. Kulkarni et al. proposed a precast connection method using nuts and bolts, while placing steel plates inside the beam and column. Numerical models were generated using DIANA, the finite-element software to study the seismic behavior. Vidjeapriya and Jaya examined the effect of J-Bolts and cleat angles on the hysteretic behavior of precast beam–column connections. They realized that using J-Bolts for the beam–column connection leads to higher ductility as well as energy dissipation in comparison to similar monolithic specimens, while using cleat angles for the connections leads to less ductility. Alias et al. investigated the performance of grouted sleeve connectors in different conditions [11-14]

*Testing arrangements*

Eight numerical models with the same geometry, but different materials and joints were analyzed. In this set of models, two of them are without couplers, and six models were pinned with couplers in a beam-column joint. lightweight concrete constructed from Leca, couplers, length of couplers and strength of grout were the variables of this assessment

*Specimen's details*

In the present study, the joint is cruciform and the columns and beams have the same dimensions of 30cm * 30cm. Figure 1 demonstrates the length and height of the model and the loading conditions. Table 1 shows the details of the specimens that were utilized in this study.

## Material Properties

Since the studied structures are cruciform reinforced concrete beam-column joints, the properties of beam and column elements are as follows. Yielding strengths are 4000 kg/cm2 and 3000 kg/cm2 for longitudinal and latitudinal rebars, respectively. According to the CMI-8606234 guideline published by Leca Company, the mix design for Leca structural and concrete properties of Leca material used in structural lightweight concrete are mentioned in table 2 and 3 respectively. This lightweight concrete from Leca has been determined to have an elastic modulus of 14.5 GPa. As mentioned earlier, the joint zone grout is one of the variables in this study.





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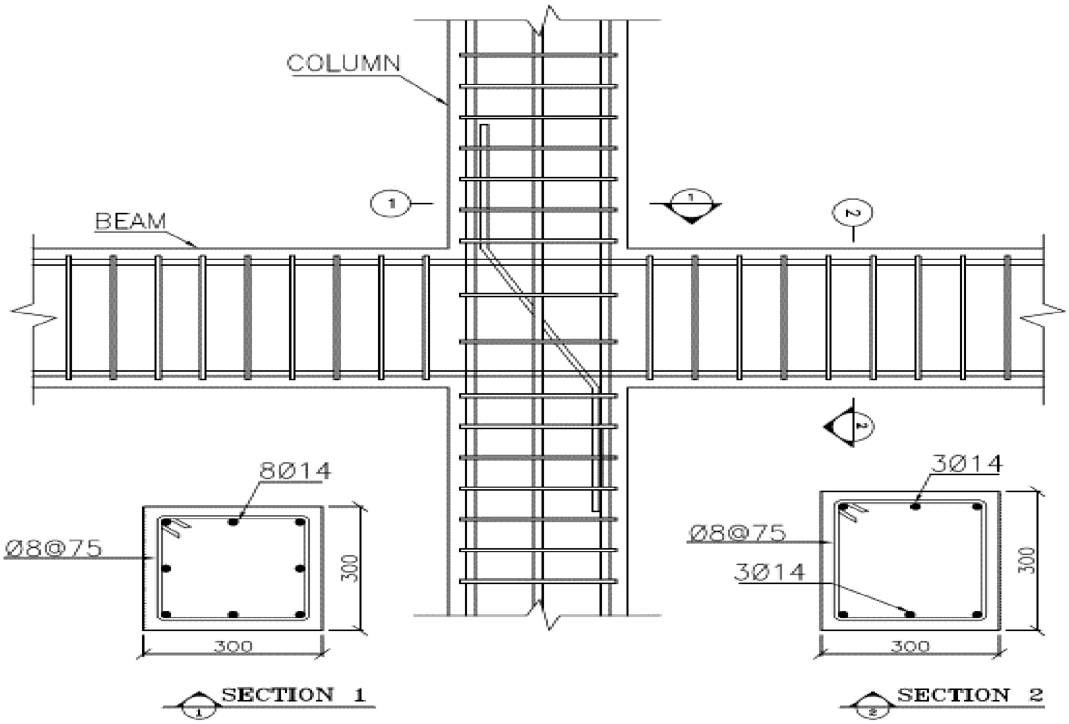


**Fig. 1.** Dimension of the specimens

In this regard, two compressive strengths of fc=30 MPa and fc= 20 MPa were considered for the first and second grout, respectively.

*Numerical model*

For the analysis, the finite element method was applied using Abaqus software. Three structural models have been developed for analyzing concrete under low pressure as follows:

- Smeared crack (SC) model
- Brittle cracking (BC) model
- Concrete damaged plasticity (CDP) model

The CDP model is based on isotropic damage. The model is designed to represent concrete under various loading conditions, such as uniform and cyclic. The CDP model considers the effects of a reduction in elastic stiffness and plastic strains (in both tension and compression) as a result. Furthermore, it considers the effect of stiffness recovery under cyclic loading conditions. Using this behavioral model, concrete properties are defined separately in tension and compression. A review of the leading studies that have modeled concrete in Abaqus reveals that they applied the CDP behavioral model in most cases. Therefore, the present study was conducted using this model. The failure criteria and the yielding function of this model are Drucker-Prager and Lubliner, respectively. Eight-node elements (C3D8) and damaged plastic material were for modelling concrete in Abaqus. In this numerical mode, reinforcing elements are represented by metal plasticity models. By this modelling approach, the behavior of concrete is assumed to be independent of the reinforcing elements. The tensile hardening parameter of concrete defines integration effects between rebar and concrete for simulating load transfer in cracks rebars' direction. Besides, the T3D2 truss element was used for modelling the longitudinal and latitudinal rebars. This three-dimensional element is a two-node element with linear deformation. The truss elements are embedded in concrete and demonstrate integrated behavior. The modelled column was pinned at the lower bound and its free end was under quasi-static cyclic lateral loading applied by a loading cap. In the internal joint sample, the beams were rolled at both ends with restrictions on degrees of freedom of translation along the axis perpendicular to the lateral loads. Two types of loading were applied on the sample. The first type was axial loading of 22.5 and 11.25 tons, and the second type was cyclic loading. The following diagram shows the cyclic loading condition. This joint was analyzed using a quasi-static method. Figure 2 shows the loading protocol. Figure 3 shows the loading conditions in Abaqus software.

*Numerical Observation and Results*

The comparison of the hysteresis curves and back bone curves for 8 models is shown in Figure 4 and 5 respectively. According to the results of the analytical diagram, load and displacement of the models in yield and ultimate situation is shown in table 4.




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Energy absorption capacity of the evaluated joints depends on the area under the load-displacement diagram after each loading cycle. This area indicates the criticality of joints under seismic loading. According to the results, this joint is adequate in terms of energy absorption without a reduction in strength and stiffness. The residual area under the load-displacement diagram for each cycle was calculated in order to evaluate the energy absorption behavior of the studied samples. Using this approach, a diagram of energy absorption versus relative lateral displacement can be obtained for each loading cycle. Employing dimensionless energy absorption systems is essential due to the different strengths of the materials, which leads to different fractures in terms of loading and displacement. The following approach is required for obtaining dimensionless energy absorption in each cycle:

$$\text{Normalized Energy Dissipation (NED)} = \frac{A}{4V_{max}\delta_{max}}, \quad (1)$$

The steps mentioned earlier are applied to all samples based on the number of loading cycles. For each cycle, certain points of dimensionless energy absorption are determined. By crossing the most optimum curve from the specified points, the diagrams in Figure 6 are derived.

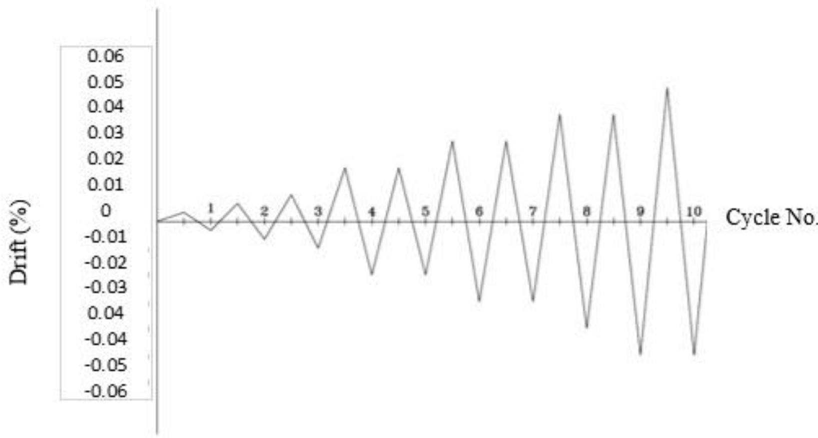


**Fig. 2.** Loading Protocol

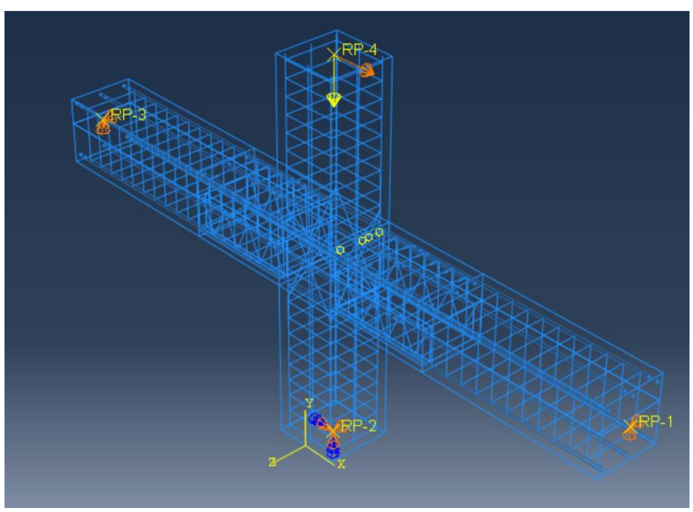


**Fig. 3.** Loading Conditions





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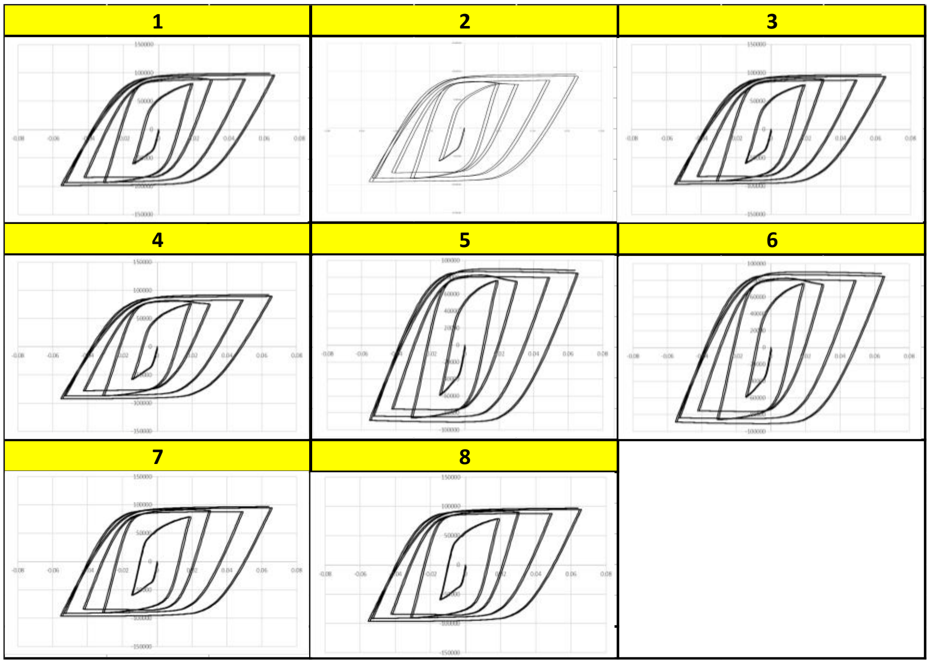


**Fig. 4.** Numerical hysteresis Curves

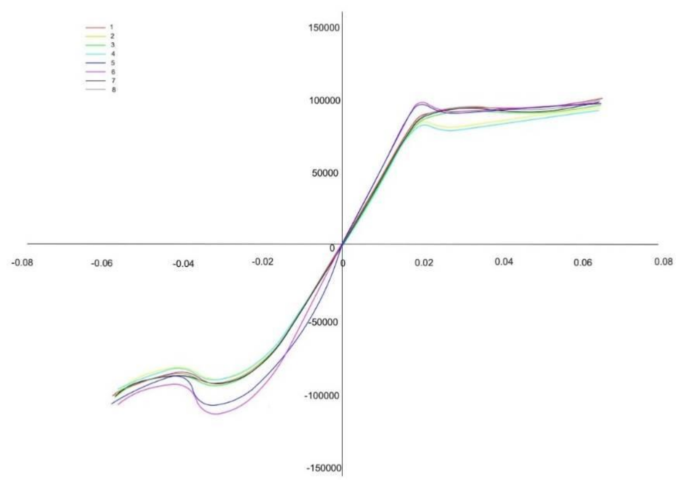


**Fig. 5.** Back bone Curves

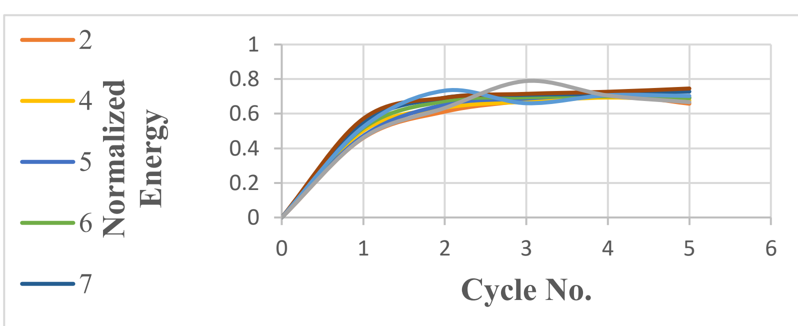


**Fig. 6.** Dimensionless absorption diagram





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**Table 1**. Test specimens' Details

| Model name | Normal concrete strength (MPa) | Grout strength (MPa) | Axial Load (Ton) | Notes |
|---|---|---|---|---|
| 1 | 25 | - | 11.25 | Beam and column are made by conventional concrete without couplers |
| 2 | 25 | 30 | 11.25 | Beam and column are made by conventional concrete conventional grout without couplers |
| 3 | 20 | 30 | 11.25 | Connection zone is grouted, and couplers are located at 500 mm of column face. |
| 4 | 20 | 20 | 11.25 | Connection zone is grouted, and couplers are located at 500 mm of column face. |
| 5 | 20 | 30 | 11.25 | Connection zone is grouted, and couplers are located at 375 mm of column face. |
| 6 | 20 | 20 | 11.25 | Connection zone is grouted, and couplers are located at 375 mm of column face. |
| 7 | 20 | 30 | 22.5 | Connection zone is grouted, and couplers are located at 375 mm of column face. |
| 8 | 20 | 20 | 22.5 | Connection zone is grouted, and couplers are located at 375 mm of column face. |

**Table 2**. Mixed design for leca structural concrete

| Mix design for Leca structural concrete | Leca (kg/m3) | Cement grade (kg/m3) | weight of sand (kg) | W/C | Additive percent |
|---|---|---|---|---|---|
| LC2 | 2500 | 400 | 800 | 0.64 | ----<br>------- |

**Table 3.** Compressive strength of leca structural concrete

| Compressive strength | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mix design** | LC2 | | | | | | |
| **Age (Day)** | 2 | 3 | 5 | 7 | 14 | 28 | W (kg/m3) |
| **Concrete (Mpa)** | 8.4 | 11.2 | 13.9 | 18.1 | 18.5 | 20.4 | 1772 |





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**Table 4.** Back Bone Curve Results

| Cycle No. | Fy (N) | Δy (m) | Fu (N) | Δu (m) | K (kN/m) | μ |
|---|---|---|---|---|---|---|
| **1** | 69,676 | 0.01625 | 98,875 | 0.0593 | 4287.75 | 3.65 |
| **2** | 66,580.5 | 0.0159 | 92,526 | 0.0596 | 4187.45 | 3.75 |
| **3** | 68,896.5 | 0.01655 | 95,128 | 0.0598 | 4162.93 | 3.61 |
| **4** | 66,794 | 0.01665 | 90,776.5 | 0.0601 | 4011.65 | 3.61 |
| **5** | 66,907 | 0.0158 | 86,487.5 | 0.0601 | 4234.62 | 3.80 |
| **6** | 66,794 | 0.0156 | 84,844.5 | 0.0599 | 4281.67 | 3.84 |
| **7** | 67,206.5 | 0.01625 | 95,108.5 | 0.0601 | 4135.78 | 3.70 |
| **8** | 68,866 | 0.016 | 94,367 | 0.0600 | 4304.13 | 3.75 |

## Conclusion

In this numerical study, the rigid behavior of prefabricated beam-column joints has been investigated. Therefore, this study investigates the effect of lightweight concrete on the flexural rigidity of prefabricated beam-column joints the following results were obtained after analysis of the various models and comparing their load-displacement diagrams, initial stiffness, energy absorption, and failure modes:

1. The effect of lightweight concrete on joints is negligible. Additionally, grout type significantly affects the joint zone. By variation in the strength of grout in the joint zone, the ductility and strength of the structure are directly affected.
2. However, the effect of lightweight concrete is negligible, it results in reducing cement consumption and thereby leading to cost efficiency.
3. Based on the comparison of samples with and without pins, and with the same grout and concrete, it was concluded that variations in pin length had no considerable effect on the joint.
4. Variations in the applied lateral load to the column caused insignificant changes in the stress contours. Additionally, more stress was observed in the joint zones of samples with higher loading.

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