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Evaluation of Ductility of Precast Column Foundation Connections

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Abstract

Objectives: To investigate and compare the ductility performance of precast column foundation connection using the method proposed by Park and ASCE 31-03. **Methods**: Strength and ductility are the most important parameters to resist earthquake forces for the overall safety of a structure. Evaluating ductility from experiments is a cumbersome process. From the experimentally obtained load-displacement envelope, the ductility was evaluated for four specimens of precast column foundation connection by the method proposed by Park and Paulay (1989) and ASCE 31-03. The results were also compared with monolithic specimen. Each of the specimen was subjected to displacement-controlled lateral cyclic loading. The maximum displacement was maintained at 40 mm due to laboratory constraints. **Findings**: From the evaluated results, ASCE 31-03 gives better values of ductility than the method proposed by Park. The calculated ductility by ASCE 31-03 were 31.5 %, 41.07 %, 72.7%, 68.3% and 48.9 % higher for monolithic specimen, PCBJ, PC I, PC II and GS specimen respectively. **Novelty**: The present study reveals the best-suited method that can be applied to evaluate ductility for specimen subjected to lateral cyclic loading that has not been reported in earlier studies.

Keywords: Ductility Ratio; Yield Displacement; Ultimate Displacement; Precast Connection; Load Displacement Envelope

1 Introduction

Displacement ductility is an important parameter used to evaluate the seismic performance of structures[1]. The structures need to be designed to have sufficient strength and ductility for overall safety against earthquake forces. Both the strength and the ductility are mutually associated to enhance the structural seismic safety of a structure[2]. The concept of displacement ductility is important in seismic design because it is a measure of a structure's ability to absorb energy during an earthquake. Structures with higher displacement ductility can undergo larger deformations without collapsing, which means they can dissipate more energy and are less likely to fail during a seismic event. The seismic codes and standards often specify minimum displacement ductility requirements for structures to ensure that they have sufficient capacity to withstand seismic forces. Designers can use displacement ductility to assess the seismic performance of a structure and determine whether it meets the requirements of the applicable seismic code or standard [3]. The ASCE/SEI 41-17 [4,5] evaluates ductility as the ultimate drift gained as the corresponding loading drift when the applied load fell to 80% of the maximum load. Determining the displacement ductility is a challenging task because the structural response often lacks distinct points that clearly define yield and ultimate displacements. Displacement studies have been performed to assess the dissipation capacity of precast structures using different procedures [6,7]. In the present study, the authors have addressed the variation in methods adopted to assess ductility and identified the most appropriate method for their comparison. The study findings also reported the suitability of the methods for evaluating the ductility of precast column and foundation connections. A comparative study on ductility factors on precast column foundation connection subjected to lateral reverse cyclic loading conditions has been done using the method proposed by Park (1989) [8,9] and ASCE 31-03 [10] for evaluating ductility. The values have been taken from the experimental results tested on four different specimen and compared with monolithic connection.

2 Methodology

The importance of displacement ductility lies in its ability to provide a warning before the structure fails due to an earthquake. If a structure is not designed to have sufficient displacement ductility, it may collapse suddenly and without warning during an earthquake, leading to significant loss of life and property damage. However, if a structure has sufficient displacement ductility, it will undergo large deformations before collapsing, allowing occupants to evacuate and potentially minimizing the damage to the structure itself. Displacement ductility is particularly important in earthquake-prone regions, where the ground motion caused by seismic waves can induce large forces on buildings and other structures. Building codes and design standards in these regions often require that structures have a minimum level of displacement ductility to ensure their safety during earthquakes. Overall, displacement ductility plays a critical role in ensuring the safety and stability of structures during earthquakes and other extreme events, and it is an essential consideration in the design and construction of buildings and infrastructure. An idealized procedure has been adopted to determine the ductility [7]. This study researches the underlying procedure of Park [8,9] and ASCE method [10].

2.1 Displacement ductility

The concept of displacement ductility is used to evaluate the seismic performance of structures by assessing their ability to withstand large inelastic deformations during an earthquake without experiencing significant damage or collapse. In earthquake-resistant design, the goal is to design structures that have high displacement ductility, which means that they can sustain large deformations without experiencing significant strength degradation or failure. This is achieved by designing the structure with appropriate materials, cross-sectional dimensions, and detailing, which can ensure that the structure can undergo large deformations while still maintaining its load-carrying capacity.

Displacement ductility (μ) is typically expressed as a ratio of the maximum displacement $\triangle_u$ that the structure can sustain under cyclic loading to the displacement at which significant strength degradation or failure occurs $\triangle_y$. Yield displacement ($\triangle_y$) is the displacement at which a material starts to exhibit inelastic behaviour and the stress-strain relationship becomes nonlinear. The specific value of displacement ductility that is targeted for a particular structure depends on various factors, such as the importance of the structure, the expected seismic hazard level, and the performance objectives for the structure.

$$\mu = \frac{\triangle_u}{\triangle_y}$$

2.1.1 Displacement ductility by Park and Paulay

Park's (1989) [9] displacement ductility equation, proposed in 1989, is used to evaluate the ductility of reinforced concrete structures subjected to seismic loading. Displacement ductility is a measure of the extent to which a structure is able to deform under seismic loading without experiencing damage or failure. The displacement ductility ratio provides an indication of the ability of a structure to undergo inelastic deformation, absorb energy, and resist collapse during an earthquake. A higher value of displacement ductility indicates that the structure is more ductile and better able to withstand seismic loading. Park's displacement ductility equation has been widely used in the design of reinforced concrete structures subjected to seismic loading, and it is included in many seismic design codes and standards. However, it should be noted that the equation is based on certain assumptions and limitations, and it may not be suitable for all types of structures or loading conditions. Therefore, it is important to carefully evaluate the applicability of the equation to their specific design situations and consider other factors that may affect the ductility of the structure. The ductility as per Park equation is measured from the load-displacement envelope.

The yield displacement refers to the displacement of a structure or a material at which it starts to yield, meaning it undergoes plastic deformation. Yield displacement ($\triangle_y$) is an important parameter in the design of structures because it affects the overall performance and safety of the structure. In his paper Park[(11)] describes methods to evaluate yield displacement based on various assumptions.

1. The equivalent elasto-plastic system is a simplified model used to analyze the behavior of structures subjected to loads that cause plastic deformation. The model assumes that the structure behaves elastically until it reaches the yield point, at which point it behaves plastically.

2. Reduced stiffness refers to the decrease in stiffness of a structure or material due to plastic deformation. As a structure or material undergoes plastic deformation, its stiffness decreases, which can lead to increased deformation and instability.

3. Secant stiffness is a measure of the stiffness of a material or structure under a given load. It is calculated as the slope of a secant line drawn between two points on the load-deformation curve.

4. The ultimate lateral load refers to the maximum load that a structure can withstand before failure. The nonlinear elastic behaviour before the first yield or 0.75 P (P- is the peak load), refers to the behavior of reinforced concrete structures before they reach their ultimate lateral load. During this stage, the concrete may exhibit cracking and other forms of non-linear behavior.

The ultimate displacement can be measured based on various assumptions:

1. The displacement corresponding to the peak of the load-carrying capacity refers to the maximum displacement that a structure can withstand under a given load before it fails. This displacement is typically referred to as the peak displacement or maximum displacement.

2. The post-peak displacement is the displacement that occurs after the peak load-carrying capacity has been reached and the load-carrying capacity has undergone a small reduction, such as a 20% reduction in load. This displacement is also known as residual displacement, and it is typically less than the peak displacement.

3. The displacement when the material fractures or elements buckle refers to the displacement that occurs when the material or structural elements of a structure fail due to excessive loading. In the case of reinforced concrete, this could refer to the displacement that occurs when the transverse or longitudinal reinforcing steel fractures or the longitudinal compression reinforcement buckles. This displacement is typically referred to as the failure displacement or ultimate displacement.

In this paper, the authors have assumed the ultimate displacement as the value corresponding to the maximum displacement the structure can withstand (Figure 1). The load corresponding to this displacement is assumed as 85% of the peak load. The yield load P_y is taken as 75% of peak load and the displacement corresponding to this load is considered as yield displacement.

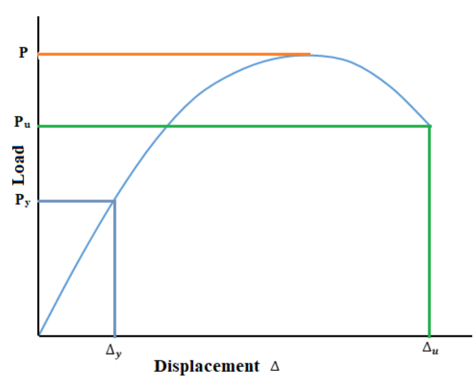

Fig 1. Evaluation of ductility by Park & Paulay (1989)

2.1.2 ASCE 31-03 method

ASCE (American Society of Civil Engineers) guidelines provide specific requirements and recommendations for calculating displacement ductility and other seismic design parameters for different types of structures. In ASCE 31-03[(10,11)] Seismic evaluation of buildings, ductility is measured as specified below:

Peak load (Pmax) is the maximum load that a structure can sustain before collapsing, while yield load (Py) is the load at which the structure begins to exhibit inelastic behavior. It is taken as 85% of the peak load. The corresponding displacement (Du) on the load-displacement curve is the displacement at which the peak load is reached. Yield displacement (Dy) is taken as

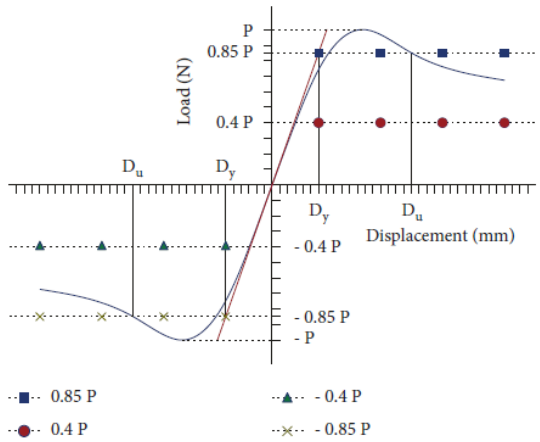

Fig 2. Evaluation of ductility by ASCE 31 – 03

the displacement corresponding to yield load (Py) (Figure 2). In seismic design, the displacement ductility ratio is an important parameter that helps to ensure that a structure can deform sufficiently during an earthquake to absorb the energy of seismic waves and reduce the risk of collapse. ASCE (American Society of Civil Engineers) guidelines provide specific requirements and recommendations for calculating displacement ductility and other seismic design parameters for different types of structures.

2.2 Experimental Investigation

2.2.1 Precast column foundation connection

A study on the Seismic behaviour of various precast column foundation connection[12] was performed by applying reverse lateral cyclic loading on the specimen. The connections considered for the study include Pocket connection (PC I & PC II), base plate connection (PCBJ) and grouted sleeve connection (GS). The results of all the connections were compared with monolithic connection (ML) for the same loading condition. The ductile detailing as per IS 13920[13] of all the specimens are shown in Figures 3, 4, 5, 6 and 7.

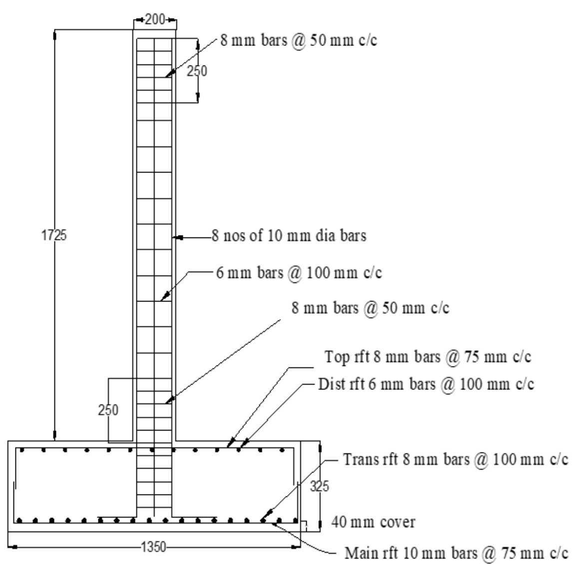

Fig 3. Monolithic connection (ML) detailing

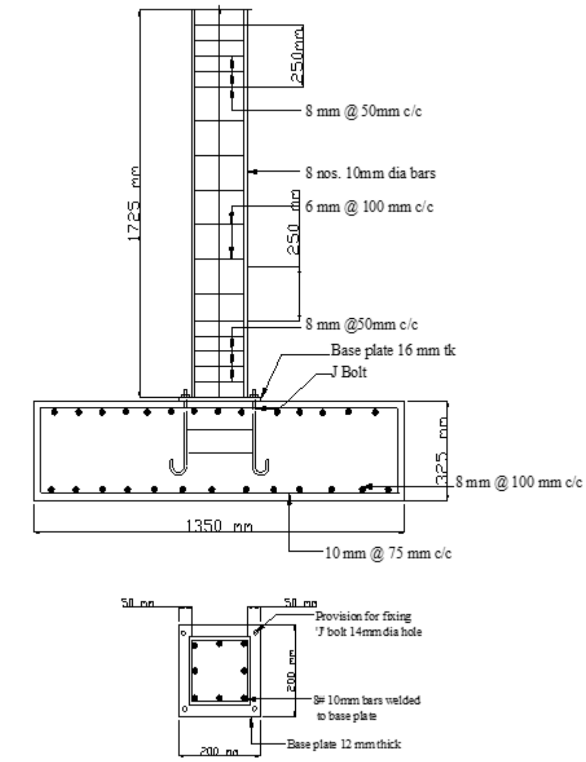

Fig 4. Base plate connection (PCBJ) detailing

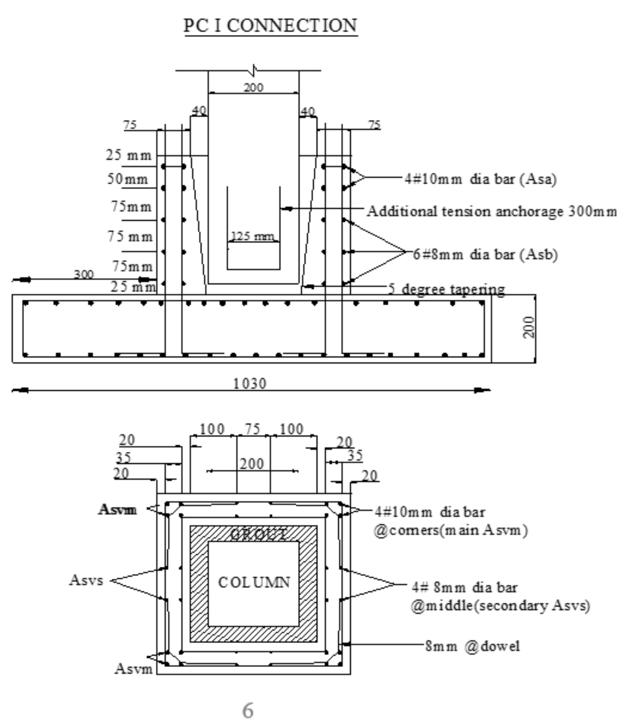

Fig 5. Pocket connection (PC I) detailing

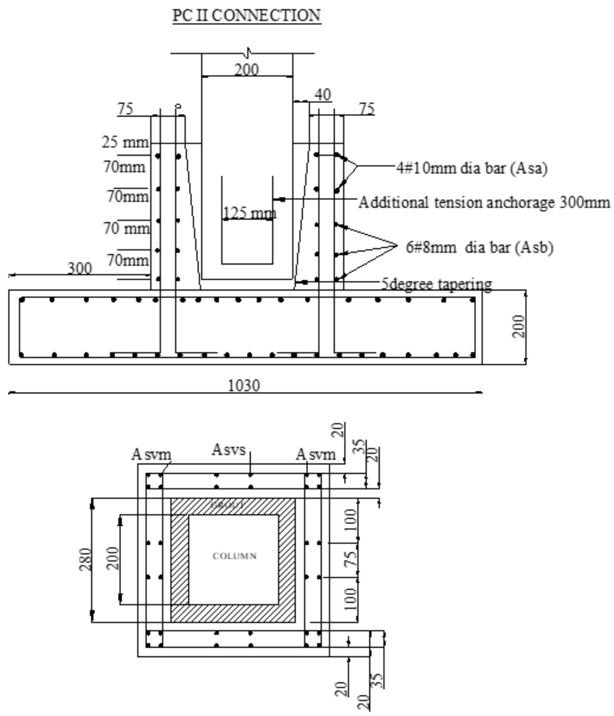

Fig 6. Pocket connection (PC II) detailing

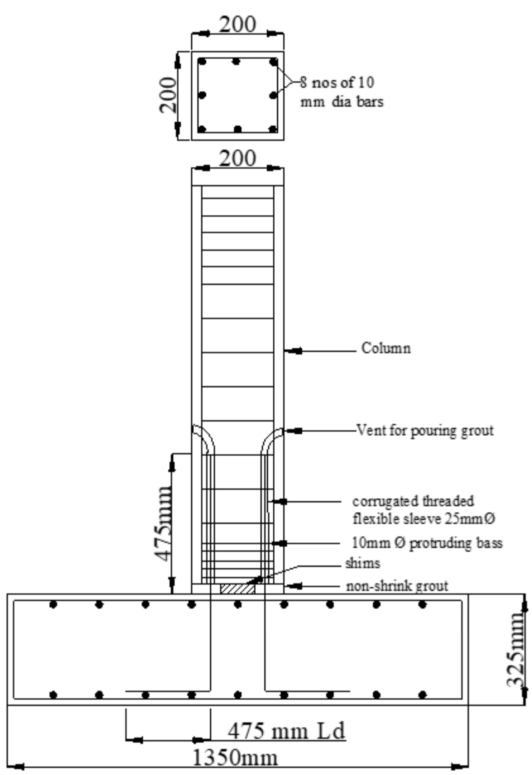

Fig 7. Grouted sleeve connection (GS) detailing

The specimens were subjected to reverse cyclic loading condition to study their performance due to seismic forces. During a lateral cyclic loading event, the precast column experiences repeated lateral displacement and rotation, which can cause bending and shear stresses in the connection with the foundation. These stresses can lead to fatigue damage over time, which can compromise the structural integrity of the connection and lead to failure. Of the parameters studied, ductility is an important characteristic that can help prevent catastrophic failure during the event of an earthquake

The load-displacement envelope is given in Figure 8, obtained from the experimental results were used to calculate the ductility of the connection.

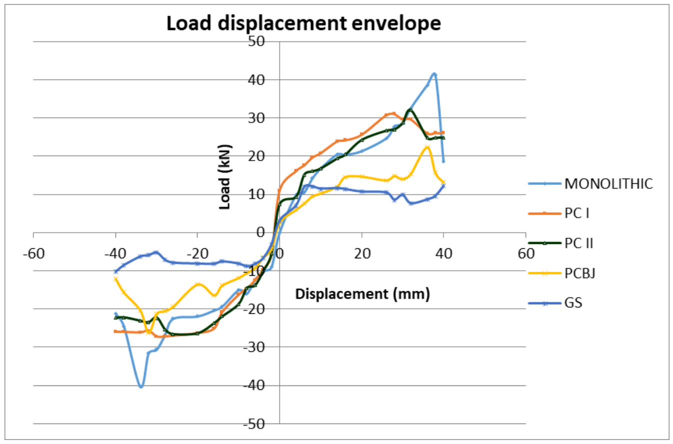

Fig 8. Load-displacement envelope of all specimen

2.2.2 Ductility based on method proposed by Park

In the study considered the ductility of the connections was assessed by the methodology proposed by Park[11]. The load-displacement envelope from the experimental data was used to calculate the ductility ratio. The results of the study are tabulated in Table 1.

Table 1. Ductility ratio of precast column foundation specimen as per Park (1989)

Specimen	**Yield displacement (Δ_y) mm**		**Ultimate displacement(Δ_u) mm**		**Displacement Ductility factor $\mu = \Delta_u / \Delta_y$**		**Average ductility factor (μ)**
	Positive	Negative	Positive	Negative	Positive	Negative	
Monolithic	20	20	39.35	35.94	1.967	1.797	1.882
PCBJ	10	10	41.04	40.56	4.104	4.056	4.08
PC I	14	16	40.00	39.19	2.857	2.449	2.653
PC II	14	14	40.00	39.89	2.857	2.849	2.853
GS	8	9	40.03	40.00	5.00	4.44	4.72

2.2.3 Ductility based on method specified in ASCE 31-03

From the load-displacement envelope, the ductility values were calculated as described in ASCE 31-03. The load-displacement curve for each of the specimen was used to arrive at the ductility for the respective specimen and is shown in Figures 9, 10, 11, 12 and 13.

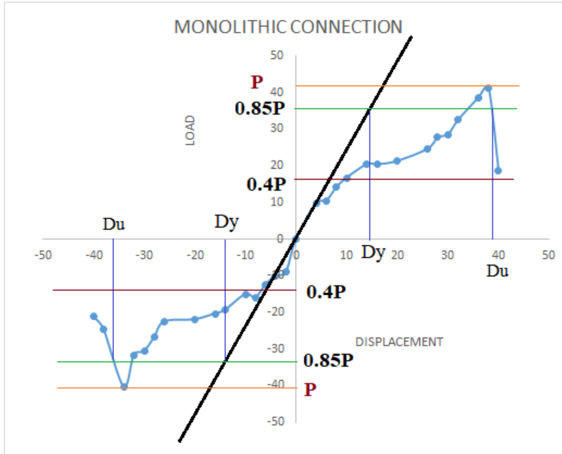

Fig 9. Ductility evaluation of ML by ASCE 31-03

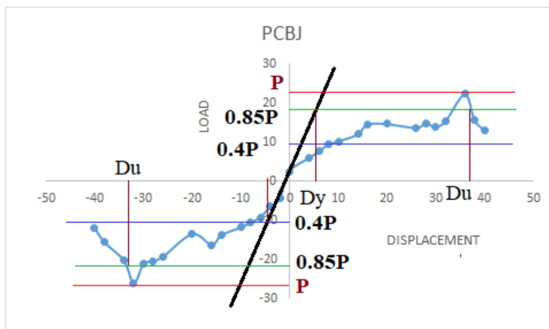

Fig 10. Ductility evaluation of PCBJ by ASCE 31-03

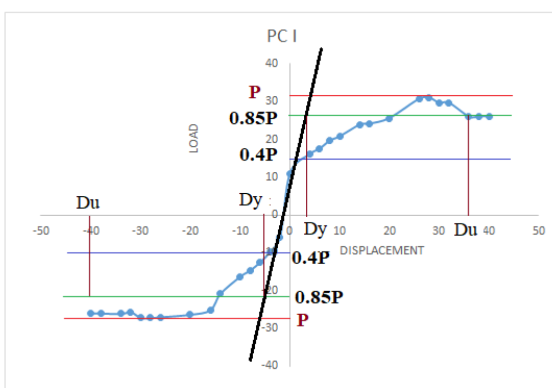

Fig 11. Ductility evaluation of PC I by ASCE 31-03

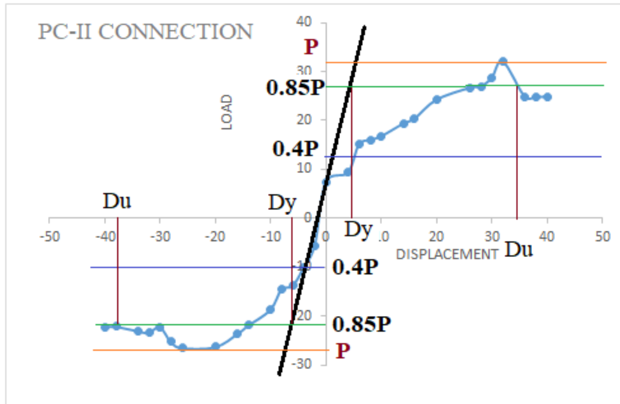

Fig 12. Ductility evaluation of PC II by ASCE 31-03

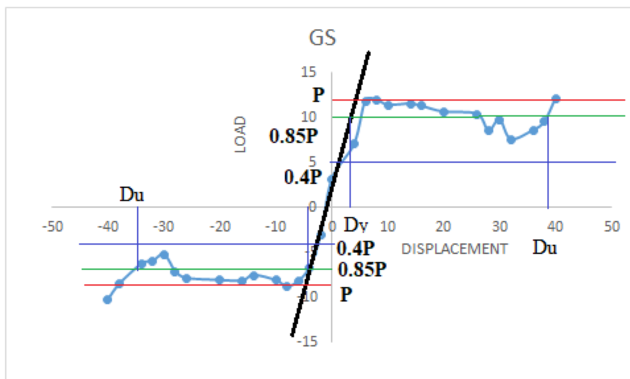

Fig 13. Ductility evaluation of GS by ASCE 31-03

The results of the calculated values are tabulated in Table 2.

Table 2. Ductility ratio of precast column foundation specimen as per ASCE 31-03

Specimen	Yield displacement (Δ_y) mm		Ultimate displacement(Δ_u) mm		Displacement Ductility factor $\mu = \Delta_u / \Delta_y$		Average ductility factor (μ)
	Positive	Negative	Positive	Negative	Positive	Negative	
Monolithic	14	14	39	38	2.78	2.71	2.75
PCBJ	5	4	37	32	7.4	8	7.7
PC I	4	4	38	40	9.5	10	9.75
PC II	5	5	35	37	7	7.4	7.2
GS	4	4	39	35	9.75	8.75	9.25

3 Results and Discussion

The yield displacement and ultimate displacement were evaluated from the load-displacement envelope by both the procedures explained above. The ductility was calculated as $\frac{\Delta_y}{\Delta_u}$. From the evaluated results, the ductility was compared for the precast column foundation connection for various connection detailing. The exact value of the ductility factor that is considered a good performance due to seismic forces can depend on a variety of factors, such as the type of structure, the level of seismic hazard, and the desired level of performance. However, in general, a ductility factor of at least 3 is often considered to be indicative of good performance under seismic loading. From the results obtained the precast connection provided a higher value of ductility than the monolithic connection, especially by ASCE method. The difference in ductility values is provided in Table 3.

Table 3. Comparison of ductility values by method proposed by Park and as given in ASCE 31-03

Sl.No	Specimen	Ductility ratio		Difference in percentage (%)
		Park (1989)	ASCE 31-03	
1	Monolithic connection (ML)	1.882	2.75	31.5
2	Base plate connection (PCBJ)	4.08	7.7	47.01
3	Pocket connection (PC I)	2.653	9.75	72.7
4	Pocket connection (PC II)	2.853	7.2	60.3
5	Grouted sleeve connection (GS)	4.72	9.25	48.9

From the results, it is understood that the ASCE 31-03 method gives a higher value than the proposed methodology by Park (1989). ASCE 31-03 guidelines follows displacement-based approach to estimate the performance level of a building and recommends a minimum ductility ratio for different performance levels. Park's proposed methodology, on the other hand, is based on the capacity design concept and aims to provide a more accurate estimation of the actual ductility capacity of reinforced concrete structures under seismic loads. It takes into account the material properties, structural geometry, and detailing of the reinforcement, and provides a more realistic assessment of the ductility capacity of the structure. This method proposed gives validated results based on many assumptions. Ductility is an important parameter for assessing a structure in the seismic zones. So, of the connections considered in this study, Pocket connection PC I & PC II can be suggested for usage in seismic zone as it is well comparable with monolithic connection based on strength. The results indicate that precast column foundation connections are more ductile compared to monolithic connection and are suitable for earthquake-resistant design.

The difference in the results obtained from these two methods can be attributed to the different assumptions and approaches used in each method. ASCE 31-03 is a simplified method that provides conservative estimates of the ductility capacity of a structure, whereas Park's proposed methodology provides more accurate estimates by taking into account more detailed information about the structure.

It is important to note that both methods have their advantages and limitations and should be used appropriately depending on the specific situation and requirements of the project. In some cases, ASCE 31-03 may be more appropriate, while in other cases, Park's proposed methodology may be more suitable.

4 Conclusion

In this paper, the ductility was evaluated for four different precast column foundation connections using two procedures; the methodology proposed by Park and Paulay (1989) and ASCE 31-03. The results of the study were tabulated and compared with that of monolithic connection. From the obtained results tabulated in Tables 1 and 2, it is seen that there is an erratic difference in the calculated ductility from both methods. The following points can be deduced from the calculated values.

1. In the case of monolithic connection, both methods provided a calculated value of less than 3, which concludes that the connection is not so ductile. It can be understood that the monolithic connection offers high rigidity between the column and foundation.
2. In base plate connection (PCBJ), ductility calculated by Park method is 4.08 and that by ASCE is 7.7. The connection can be adopted very well in seismic zones. From the load-displacement curve, it is understood that the column transfers the load to the base plate once yielding has started and base plate transmits the load to the foundation through the anchoring bolts and there is a large deformation in the inelastic phase before failure can take place.
3. In the case of pocket connection PC I and PC II, it can be seen that the ductility by Park method is less than 3, which gives an understanding that the connection is similar to a monolithic connection. Whereas the ductility as calculated by ASCE method gives a value 9.75 and 7.2 respectively. It shows that the pocket connection has the capability to undergo large deformation in the inelastic zone, paving the way to behave well during a seismic activity.
4. In the grouted sleeve connection (GS), though the ductility values are high, the strength of the specimen is less compared to all the other specimen. It provides an understanding that the connection can be used in seismic zones and there is always a warning before the collapse of the system.

It is important to note that the ductility factor is just one of many factors that contribute to the seismic performance of a structure, and it should be considered in conjunction with other factors, such as strength, stiffness, and energy dissipation capacity. Additionally, the desired level of performance for a given structure may vary depending on its intended use and occupancy, and it is important to consider the specific requirements and constraints of each design situation.

The present study provides an understanding to researchers to adopt the best-suited method to evaluate ductility. However, the study has been limited to ductility evaluation by two methods only. Further research can be performed to verify the benefit of other methods considering several other parameters that influence ductility.

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References

1) Beni MB, Madhkhan M. Experimental study on two innovative ductile moment-resisting precast concrete beam-column connections. 2022. Available from: https://doi.org/10.1016/j.istruc.2022.03.059.
2) Resatoglu R, Jkhsi S. Evaluation of Ductility of Reinforced Concrete Structures with Shear Walls having Different Thicknesses and Different Positions. *IIUM Engineering Journal*. 2022;23(2):32–44. Available from: https://doi.org/10.31436/iiumej.v23i2.2070.
3) Tang L, Tian W, Guan D, Chen Z. Experimental Study of Emulative Precast Concrete Beam-to-Column Connections Locally Reinforced by U-Shaped UHPC Shells. *Materials*. 2022;15(12):4066. Available from: https://doi.org/10.3390/ma15124066.
4) ASCE/SEI 41-06 A. A New Seismic Rehabilitation Standard, American Society of Civil Engineers: Reston, VA, USA, 2017. Reston, VA, USA. American Society of Civil Engineers. 2017.
5) Senturk M, Pul S, Ilki A, Hajirasouliha I. Development of a monolithic-like precast beam-column moment connection: Experimental and analytical investigation. *Engineering Structures*. 2020;205:110057. Available from: https://doi.org/10.1016/j.engstruct.2019.110057.
6) Belleri A, Labò S. Displacement-based design of precast hinged portal frames with additional dissipating devices at beam-to-column joints. *Bulletin of Earthquake Engineering*. 2021;19(12):5161–5190. Available from: https://doi.org/10.1007/s10518-021-01169-y.
7) Vielma-Perez J, Mulder M. Improved procedure for determining the ductility of buildings under seismic loads. 2018. Available from: https://doi.org/10.23967/j.rimni.2018.03.001.
8) Ductility evaluation from laboratory and analytical testing. In: Proceedings of Ninth World Conference on Earthquake Engineering. 1988;p. 605–616.
9) Park R. Evaluation of ductility of structures and structural assemblages from laboratory testing. *Bulletin of the New Zealand Society for Earthquake Engineering*. 1989;22(3):155–166.
10) 31-03 A. Seismic Evaluation of Existing building, New York, USA, 2002. New York, USA. 2002.
11) Balasubramanian K, Jaya KP. Reverse Cyclic Loading Effect on RCC Wall-Floor Slab-Deep Beam Connection. *Advances in Civil Engineering*. 2022;2022:1–14. Available from: https://doi.org/10.1155/2022/8497173.
12) Hemamathi L, Jaya KP. Behaviour of Precast Column Foundation Connection under Reverse Cyclic Loading. *Advances in Civil Engineering*. 2021;2021:1–17. Available from: https://doi.org/10.1155/2021/6677007.
13) IS 13920-1993: Indian Standard ductile detailing of Reinforced Concrete Structures subjected to Seismic forces, Bureau of Indian Standards. .