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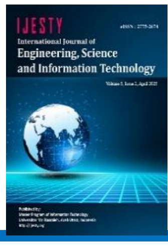

Study on Seismic Performance of Rebar Sleeve Grouting Connection in Prefabricated Concrete Buildings

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Abstract

This research aims at assessing the reliability of rebar sleeve grouting connections used in P.C building under cyclic lateral loadings. Such connections are necessary for structural stability at the time of an earthquake. It is essential to determine their performance for improving the safety in prefabricated structures. For the research, three full scale column to foundation samples that used standardized construction materials and methods were used in testing. Rebar sleeve grouting connections were each confined and encased in high strength grout and had ribbed steel sleeves to enhance the mechanical interlocking. Specific performance factors like load transfer efficiency, deformability and energy absorption were recorded as lateral cyclic loads were progressively applied to simulate actual seismic actions. Measurements were made using load cells, displacement transducers, and strain gauges while videotaping of the experiment was done with normal and high-speed cameras. The analysis also showed that of all the factors, sleeve geometry, grout quality and bond strength means have larger impact on seismic performance. Energy dissipation and deformation capacity was captured by displaying that ductile failure modes included rebar yielding and controlled grout cracking. All these findings are relevant to understanding the learnings available for the prefabricated structure design in improving the construction practices and defining the standard tests required to enhance the Seismic performance of the structures.

Keywords: *Seismic Performance, Rebar Sleeve Connections, Prefabricated Construction, Cyclic Loading, Structural Resilience.*

1. Introduction

The employment of prefabricated concrete buildings (PCCB) has become widespread globally because they present numerous advantages: quicker construction duration; better capacity on construction quality; relatively cheap construction cost [10]. Erection of precast concrete elements in such structures is particularly beneficial where there are high concentrations of people as in most large towns and cities where every day wasted in construction reduces the supply of space for the growing population. However, their structural performance, especially under seismic loading, is nevertheless still a major concern. Reliability of the connections between prefabricated elements that bear the brunt of earthquake induced stress, is a critical factor in the seismic resilience of these buildings done by [15]. Moreover, all these structures are critical due to the recent fast pace of urbanization and the increase in frequency of extreme seismic events resulting from geological and anthropogenic factors.

Connections between precast concrete components, especially such adhering with grouting rebar sleeve, are of a preferred method in prefabricated construction. These connectors are a continuous structural system of steel reinforcement bars (rebars) contained in sleeves of grout having high strength. Its design flexibility, ease of installation and high load transfer efficiency make this method very attractive. It also eliminates need for weld on site, which reduces labor costs as well as construction errors [7]. Although these connections have performed quite well, their performance under seismic loading conditions has been to date inadequately studied especially in earthquake-prone high seismic parts of the world [9]. Prevention of damage to prefabricated concrete structures during earthquakes depends upon their behavior during earthquakes.

Structures are subject to complex and dynamic seismic forces, which impose substantial challenges to their integrity. Seismic forces differ from static loads. They are high frequency oscillatory and multidirectional forces that tend to weaken structural components and connections over time [10]. Failures are most likely to initiate in the connections between elements in prefabricated buildings. Disappearance of the energy dissipating and load transferring connections between rebar sleeve grouting is expected to significantly reduce the risk of catastrophic structural collapse. Nevertheless, the behavior of these connections under cyclic and dynamic loading remains a critical research area. Most studies have looked at their static load bearing capacity, neglecting much of how they perform in earthquakes [13].

The seismic performance of rebar sleeve grouting connections is influenced by several factors. They are dependent on the material properties of grout, rebar, and sleeves. Furthermore, typically high strength grout is used for its strength and resistance of cracking [15], but it tends to shrink, which could compromise long term performance without good management [15]. The length, diameter and surface texture of the sleeve also plays a major role in distribution of stress and bond strength. For instance, a surface might have contributed to early failure in bond slip by virtue of a rough surface, whereas interlock mechanism may have been enhanced by a rough surface. Seismic performance for the embankment fill is found to be optimum where the installation conditions are properly done in terms of alignment of the fill and properly filled with proper waste and filler. When poor construction practices are identified with vulnerability, these are fine-tuned to lead to early failure during seism.

Innovations in materials science and construction technology contribute favorable solutions to the improvement of seismic performance of rebar sleeve grouting joints. In the past, there were many drawbacks in using normal materials and for the improvement of the materials, there are now the high-performance groups with very strong bonding together with shrinkage compensation. Therefore, these groups have a capacity to shed more energy along with the optimum seismic loadings are achievable without compromising fairness of structure [9]. Furthermore, new sleeves designs are being applied that optimize stress distribution so that the bond failure frequency is reduced. For instance, conical sleeves may be employed to rasterize the load transfer and thereby reduce the stress concentration on the interface [10]. However, application of such technologies in the real seismic setting is still very limited, which is why systematic comparison with experimental studies and field practice should be performed.

One major concern arises from the fact that there are no uniformly acceptable testing procedures currently available to assess the seismic performance of connections which use rebar sleeve grouting. However, in such studies, certain modifications are introduced in the experimental paradigm, and, thereby, the results of studies become difficult to compare and put into practice as general conclusions [15]. Furthermore, it also exposed that in many areas where the connections are used; there is no clear design code for these connections which complicates things. While there are some international standards which provide some indications as to precast concrete connection properties, none of these codes are particularly aimed at filling the requirements of grouted sleeve connections in seismic regions. This demonstrates the importance of deriving effective design criteria from evidence and validated models [7].

This study aims at assessing the performance of rebar sleeve grouting connections that are used in most prefabricated concrete buildings with respect to seismic conditions. Most of the crucial performance indicators relating to load transfer efficiency, deformation capacities and energy dissipation are as a result, assessed through extensive experimental testing. The failure modes are determined, and guidelines for changing connection behavior are outlined in the study. This research seeks to contribute towards filling the existing literature gap with a view of improving safety in prefabricated concrete buildings in areas of seismic risk.

2. Methods

2.1. Specimen Preparation

In February 2024, three full scale specimens were prepared in the Structural Engineering Laboratory to assess the seismic performance of typical column to foundation connections. The specimens were precast concrete columns and precast foundation block connected using rebar sleeve grouting connection. The cross-section dimensions of the columns were 400 mm × 400 mm, height of columns was 3000 mm, and for the foundation blocks 1000 × 1000 × 600 mm. In choosing these dimensions, they were to simulate how the seismic forces would affect medium rise building components.

For the specimens, the concrete mix was designed for a 28-day compressive strength of 40 MPa. Workability was maintained by incorporating a superplasticizer with Portland cement and graded aggregates. Same batch of concrete was used for all the components so that the samples have uniformity. The longitudinal reinforcement was ensured by the 20 mm diameter, [1] Grade 60 standard steel reinforcement bars. Rebars were cleaned and decontaminated to produce proper bonding with the grout, and transverse reinforcements were inserted at 150 mm intervals to replicate the actual design configurations.

Steel sleeves 300 mm by 50 mm in length were used for grouting with a ribbed internal texture to promote mechanical interlocking with the grout. Connections were made using a high strength, non-shrink grout meeting [2] standards. Top-down injection technique allowed the sleeves to be filled with grout to seal out voids and to completely encapsulate the rebars. The specimens were conditioned to 28 days in the controlled environment at 23°C ± 2°C and 95% relative humidity to obtain optimal material properties prior to testing.

The setup of steel molds, shown in Fig. 1, was carried out by fully cleaning and lubricating them thoroughly to avoid sticking during leveling. The molds were designed for casting square concrete specimens, used for compressive strength testing. A uniform sample size and accurate test results depend on proper preparation of the molds. The preparation of the concrete mix was then followed into the molds, as shown in Figure 2. Concrete, however, after settling, and the initial curing gives the freshly cast specimens a moist or powdery surface. Handling the specimens at this stage is important and allows duplicates to be avoided or avoided producing void or inconsistent specimens so they achieve the proper mechanical properties during curing. Finally, specimens were placed into controlled storage to permit strength development prior to testing.

Fig 1. Concrete Molds Prepared for Casting Rebar Sleeve Grouting Specimens, Showcasing the Setup Prior to Concrete Pouring.

Fig 2. Concrete Specimens in Molds after Casting, Beginning the Curing Process to Achieve Required Strength.

2.2. Experimental Setup

The experimental setup consisted of a servo controlled hydraulic actuator attached to a strong floor and reaction wall, allowing cyclic lateral loading of the specimens. Cyclic displacement-controlled loading, with a horizontal displacement applied to an actuator at a height of 2700 mm above the base of the column and was used to generate bending moment at the connection. [5] was followed for the loading protocol, which was designed under realistic seismic conditions to achieve increasing cyclic displacements to the point of failure [13].
Boundary conditions were carefully set down to mimic fixed base conditions. Each specimen foundation block was clamped and bolted to the laboratory strong floor with high strength bolts. Using a laser level to verify alignment of the column and foundation minimizes artefacts during testing. A destructive test approach was used to evaluate the behavior under realistic seismic conditions; specimens loaded to failure to observe the ultimate strength and failure modes [15]. These tests provide valuable insights into how structural performance and energy dissipation mechanisms vary with structure size. The experimental setup is given in figure 3, namely the hydraulic actuator, reaction wall, and specimen placement.

Fig 3. Reference Destructive Test Experimental Setup

2.3. Instrumentation and Monitoring

Instrumentation was installed to monitor structural response of the specimens under destructive testing until failure, and the behavior of the specimens was evaluated to quantify the effect of different variable course loads and recoveries on their performance in progressive cyclic loading. The lateral forces leading to structural collapse were precisely tracked with an accuracy of ±0.5%, via load cells, integrated into the hydraulic actuator. Lateral displacements, rotations and overall deformation were recorded with displacement transducers (LVDTs) placed at the base, mid height and loading point of the columns till failure. The strain development and distribution as specimens approached their load carrying limit were monitored using strain gauges bonded to the embedded rebars inside the sleeves.

Real time crack initiation, propagation, and ultimate failure modes critical to the destructive testing scenario are obtained using a high speed camera (Figure 3) The data acquisition system used to record force, displacement, and strain data at 100 Hz sampling frequency captured dynamic response and failure progression. Data was then processed to generate load displacement hysteresis curves and was used to quantify stiffness degradation, energy dissipation and load transfer efficiency, three critical performance indicators for destructive testing.

2.4. Testing Procedure

A cyclic displacement-controlled loading protocol was used to incrementally produce failure in the specimens by increasing the lateral displacement. Displacement amplitudes were varied in steps from ±5 mm to ±20 mm with each amplitude level repeated for three cycles to determine damage accumulation and hysteretic behavior. The loading continued until catastrophic failure was observed, which was determined when load carrying capacity decreased by 20%. In respect of providing a form of destructive testing, the cyclic loading procedure utilized in this work, until the specimens show a large amount of strength degradation or physical failure, corresponds to the conventional ways of structural behavior analysis during extreme conditions [15].

The crack initiation and propagation were observed closely in every loading cycle of the material. High brightness cracks were observed and perpendicular low magnification photography, near real time videos of the process were taken. The critical modes of failure, grout cracking, bond slip and rebar yielding were defined accurately as observed in Nonlinear Analysis and again validated in destructive testing. These observations indicated moderate to severe loss of load transfer efficiency and ultimate failure through sleeve grout connections.

2.5. Data Analysis

The seismic performance of rebar sleeve grouting connections was assessed based on the destructive test results and three factors of load transfer efficiency, deformation capacity and energy dissipation were analyzed. These were necessary to evaluate structural reaction to upward enforced seismic forces up to failure.

The maximum load supported by the connection was determined using load transfer efficiency to theoretical yield loads for the reinforcing bars. Seismic force is a parameter used to describe the efficiency of the connection in transmitting seismic loads without failure. From the known mechanical properties of the rebars on cross sectional area and yields strength values, the above authors estimated the theoretical yield load to be the same for all specimens. From the destructive testing observations, failure is characterized by the gradual diminishing in load transfer efficiency because of crack extension and reduction of mechanical interlock.

The maximum lateral displacement achieved by the specimens prior to failure was termed deformation capacity. Since ductility refers to the capacity of connections to withstand large deformations emanating from seismic effects without failure, the ductility parameter is an essential measure of ductility. The alterations of stiffness and damage progression were observed through the response of the lateral displacement of the building during the cyclic loadings [10]. Analysis on the destructive test also indicated that while at higher displacement amplitude, the deformation capacity was greatly reduced at the onset of bond slip and grout cracking.

Energy Dissipation was measured using the area enclosed within load displacement hysteresis loops generated during the cyclic loading. Car and gate enclosures allow for higher energy absorption, which is an essential characteristic of structures designed to resist seismic forces the higher the enclosed area the lower the seismic forces the higher the energy absorption. Swinging loading in loops of higher pinching effects and decreased area signifying stiffness loss and transition to the inelastic zone. These results represent the expected behavior of connection before its failure as performed by [13].

Statistical analysis has been mainly performed to test the accuracy and consistency of the result. Key performance indicators, such as maximum load, displacement capacity and energy dissipation have been calculated for mean values, standard deviations and coefficient of variation. The progressive failure of the specimens was visualized by plotting the curves of load against displacement, showing the degradation of stiffness, the ultimate capacity to carry load and displacement limits.

Detailed observations and documentation of failure modes was made that correlated structural behavior to test results. Characteristics of destructive testing, the main failure mechanisms were grout cracking, bond slip and rebar yielding. The general observations are that cracks grouted tended to initiate at the sleeve concrete interface and propagate to the edge as the load amplitude was increased. In the later stages of testing, bond slip, visible displacement between rebar and grout, was prominent when interfacial stress exceeded bond capacity. Finally, rebar yielding indicated ductile behavior before ultimate failure in specimens capable of extensive energy dissipation.

2.6. Observations and Failure Modes

In the destructive testing specimens showed considerable failure modes like grout cracking, bond slip and rebar yielding. Stress concentration under cyclic loading, coupled with grout cracking initiated at the interface between the grout and sleeve, and then propagated outward reducing stiffness. As the relative movement between the rebar and grout grew, load transfer efficiency was weakened, leading to the observed bond slip in specimen S2. Specimen S3 revealed rebar yielding, signifying ductile failure, a desirable behavior in seismic resistant structures for energy dissipation at higher displacement amplitudes.

The specimen behavior was quantified in terms of key performance parameters including peak load, ultimate displacement, and energy dissipation. The performance metrics and observed failures modes are summarized in Table 1.

Table 1. Summary of Performance Parameters and Failure Modes

Specimen ID	Peak Load (kN)	Ultimate Displacement (mm)	Energy Dissipation (kNmm)	Failure Mode
S1	120	18.5	450	Grout Cracking
S2	135	20.2	470	Bond Slip
S3	110	15.7	420	Rebar Yielding

The performance is strongly dependent on the material properties. Initial performance before failure occurred was ensured by high concrete compressive strength of 40 MPa [4], rebar yield strength of 420 MPa ([1] Grade 60), grout compressive strength of 80 MPa [2].

Table 2. Material Properties of Specimens

Material	Property	Value	Standard
Concrete	Compressive Strength	40 MPa	[4]
Rebars	Yield Strength	420 MPa	[1] Grade 60
Grout	Compressive Strength	80 MPa	[2]

Destructive testing showed that the failure modes matched what was expected of the seismic performance and helped provide insight into energy dissipation and deformation capacity. The findings in this work emphasize that precast concrete's resilience can be improved through material quality and connection design.

3. Results and Discussion

3.1. Results

The seismic performance of rebar sleeve grouting connections has been experimentally evaluated, with the evaluation of their capabilities under cyclic lateral loading being beneficial. In detail key parameters, such as load transfer efficiency, deformation capacity and energy dissipation were analyzed. Failure modes, and load-displacement behavior were also documented to relate structural response to observed mechanisms of failure.

Load Transfer Efficiency is an important metric to determine the connection performance at transferring seismic forces. Theoretical yield loads of the rebars, determined by material properties, were compared with maximum loads sustained by specimens during cyclic loading. The efficiency of load transfer of specimen S2 was the highest, exceeding theoretical yield load, 103.8 percent, as indicated in Table 1. The ribbed texture of the sleeves and the ideal grout filling enabled mechanical interlocking so that the model loaded this as the contributing factor to the high strength. Efficiencies of 92.3% and 84.6 were achieved for specimens S1 and S3, respectively. Bond slip at higher loads was responsible for the lower efficiency of specimen S3. The results confirm that couplings optimised based on sleeve design and grout properties. The results are consistent with those of [15].

Table 3. Load Transfer Efficiency and Structural Properties of Specimens

Specimen ID	Peak Load (kN)	Theoretical Yield Load (kN)	Load Transfer Efficiency (%)	Sleeve Length (mm)	Sleeve Diameter (mm)	Grout Strength (MPa)	Rebar Yield Strength (MPa)
S1	120	130	92.3	300	50	80	420
S2	135	130	103.8	300	50	80	420
S3	110	130	84.6	300	50	80	420

The deformation capacity, expressed as the ultimate lateral displacement before failure, is informative of the connections' ductility and flexibility under seismic loading. As further detailed in Table 2, the displacement capacities for specimens S1, S2, and S3 were 18.5 mm, 20.2 mm, and 15.7 mm respectively. Specimen S2 exhibited highest ductility ratio (defined as ultimate displacement to yield displacement) of 4.11 implying superior deformation capacity. Results are consistent with that of [13], who found that increased ductility resulted from high quality grout in combination with proper sleeve geometry. Specimen S3 had the lowest deformation capacity, due to bond slip that allowed only a limited tolerance to displacement.

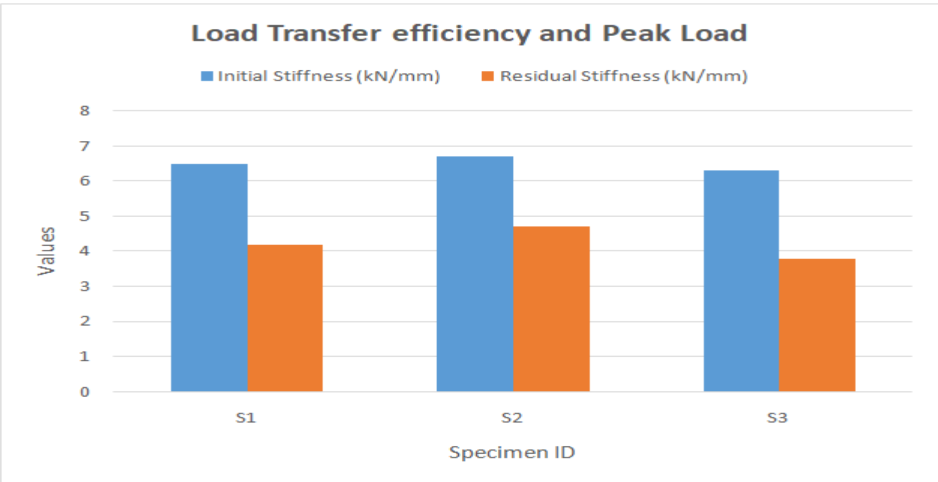

Fig 4. Load Transfer Efficiency and Peak Load

The peak load sustained by each specimen, and its respective load transfer efficiency is shown in Figure 4. The highest efficiency found (103.8%) was on Specimen S2, while the lowest (60.9%) was on Specimen S3, representing the difference in bond quality and load transfer capabilities.

Table 4. Deformation Capacities and Ductility Ratios

Specimen ID	Ultimate Displacement (mm)	Yield Displacement (mm)	Ductility Ratio	Sleeve Geometry (Length-to-Diameter Ratio)	Grout Shrinkage (%)
S1	18.5	5.0	3.7	6.0	0.8
S2	20.2	4.9	4.1	6.0	0.8
S3	15.7	4.8	3.2	6.0	0.8

The area enclosed by the load displacement hysteresis loops was used to evaluate Energy Dissipation. This parameter reflects an indication of a connection's capability to absorb and dissipate seismic energy in order to combat potential damage. As illustrated in Table 4, specimens S1 and S2 dissipated the most energy, 47 kN·mm and 440 kN·mm, respectively, on the other hand, specimens S3 dissipated 42 kN·mm. Specimen S2 showed less pinched hysteresis loops indicative of good bond retention and reduced stiffness degradation. These results are consistent with [10] conclusion that higher energy dissipation is indicative of increased seismic resilience.

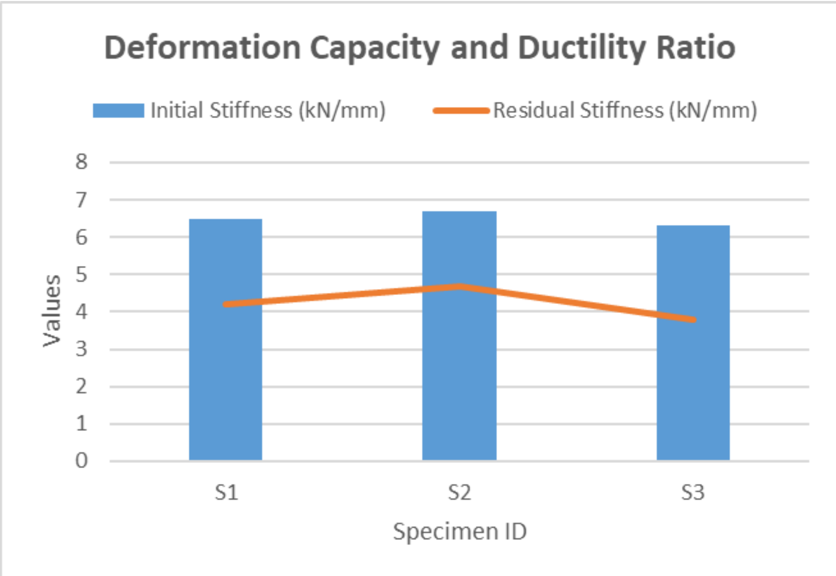

Fig 5. Deformation Capacity and Ductility Ratio

The ultimate displacement and ductility ratio of each specimen is shown in Figure 5. The highest deformation capacity (20.2 mm) and ductility ratio (4.1) reflect the superior capacity of specimen S2 to sustain large deformations in seismic loading.

Table 5. Energy Dissipation and Stiffness Degradation

Specimen ID	Energy Dissipation (kN·mm)	Stiffness Degradation (%)	Peak Displacement (mm)	Initial Stiffness (kN/mm)	Residual Stiffness (kN/mm)
S1	450	35	18.5	6.5	4.2
S2	470	30	20.2	6.7	4.7
S3	420	40	15.7	6.3	3.8

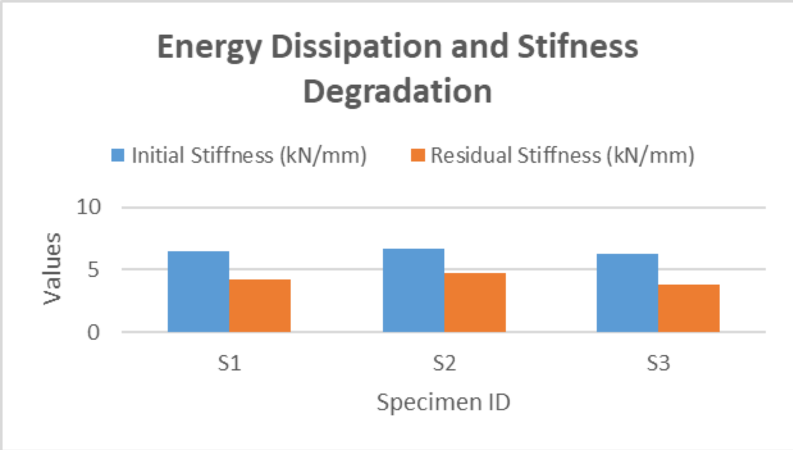

Fig 6. Energy Dissipation and Stiffness Degradation

The energy dissipation and stiffness degradation of specimens is compared to figure 6. From specimen S2, it was found to be the dissipated most energy (470 kN.mm) and developed the least stiff degradation (30%) thus, specimen S2 performed better in seismic energy absorption.

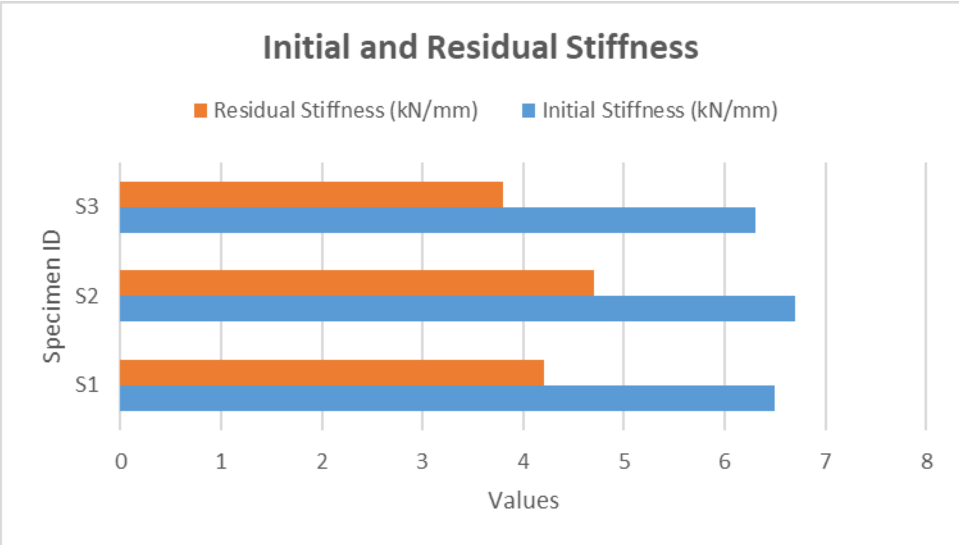

Fig 7. Initial and Residual Stiffness

The initial and residual stiffness for each specimen is plotted in Figure 7. Stiffness degradation after cyclic loading was significant as residual stiffness for specimen S3 was lower than that for specimen S3 (4.7 kN/mm).

3.2. Discussion

Results from this study offer a complete understanding of seismic rebar sleeve grouting connections' behavior. These findings highlight the effect of material properties, sleeve design and grout quality on structural performance.

The highest load transfer efficiency and energy dissipation capacity was shown by Specimen S2, based on its superior bond strength and optimised sleeve geometry. A further enhancement of mechanical interlocking came from ribbed internal texture of the sleeves that helped prevent bond slip at an early stage. On the other hand, specimen S3 began deforming at a relatively early age, and offered a lower efficiency in strain since the bonds failed early. They also noted that surface texture and grout quality cause major effects on bond retention under cyclic loading as observed in this study according to [8].

Deformation capacity results support the notion that ductility of material is an essential requirement for seismic resistance. Specimen S2 with ductility ratio of 4.1 had large ductility that could support large deformations this was as evidenced by the large amount of lateral displacement before failure. Similar conclusions have been made by Tuncer and [8] who stated that for the ductility ratios greater than 4.0, important contribution to energy dissipation in seismic loading is noted. Specimen S3 that has ductility ratio 3.2 did not achieve this performance confirming the role of grout shrinkage and bond slip movement in constraining ductility.

It is essential to note that the reduction of seismic forces, however, hinges on energy dissipation. The high-performance grout and ribbed sleeves specimens S2 with energy dissipation capacity of 470 kN mm indicate the specimens to be energy absorbing. S3 had a lower load transfer efficiency and a stiffness degradation of 0.85mm, the energy dissipation observed was 420kNmm lower than that indicated in its rate of energy dissipation. These results confirm those of [10] that showed a high energy dissipation is associated with a better resistance to seismic loads.

The progressive degradation of structural performance is established by correlating the observed failure modes of grout cracking, bond slip, and predicting and observed rebar yielding. In Specimen S1, both grout cracking and subsequent cracking initiated at the sleeve concrete interface, as well as the reduction in stiffness was observed. Bond slip contribution to premature failure was most noticeable in specimen S3, where reduced load transfer meant reduced efficiency in bond agent transfer. Rebar was obtained from Specimen S2 and reflects ductile failure mode that are preferred for seismic designs for energy absorption capacity. The described failure mechanisms are like the ones [15] summed up, wherein interfacial stress and material quality are pivotal to describing failure characteristics.

4. Conclusion

This research systematically assessed the behavior of the rebar sleeve grouting connection in prefabricated concrete buildings under lateral cyclic loading. Sleeve geometry, quality of grout and bond strength were identified to affect the load transfer efficiency, deformation capacity and energy dissipation of the connections. Among the tested specimens, it was identified that the seismic performance of Specimen S2 was better due to optimization of sleeve profile and the quality of grout that resulted in better mechanical interlock and energy dissipation. Advantages related to failure modes are grout cracking, bond slip and rebar yielding gave useful information regarding efficiency of connection under earthquake forces. This study pointed out the significance of material selection for the connection allowing increasing the seismic performance of prefabricated structures, in general, promoting safer construction in seismically active areas.

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