Half grouted sleeve connector for prefabricated structures

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Abstract— The use of prefabricated concrete systems has greatly contributed to an improvement in construction efficiency; however, connection reliability in structural components remains a major concern. This paper aims to examine the structural performance, bond behavior, and failure modes of half-grouted sleeve connectors (HGSCs) in precast column-footing connections.To achieve this objective, an experimental program involving specimens with varying embedment lengths (4d, 6d, 8d) and grout properties was carried out under axial and cyclic loads. The results of this study were analyzed to examine the load-displacement relationship, bond-slip relationship, and failure modes. Finite Element (FE) simulations using ANSYS code were conducted to validate experimental results.

From this study, it can be deduced that embedment length and grout strength significantly affect connection performance. however, an improvement in grout strength led to an improvement in stiffness but resulted in reduced ductility. This study has ascertained that HGSCs can achieve reliable and ductile performance, making them applicable to seismic and non-seismic regions.

Key words: Half-grouted sleeve connector, Precast concrete, Bond behavior, Column–footing joint, Finite element analysis, Seismic performance.

I.Introduction

Prefabricated concrete construction has emerged as a highly efficient and sustainable alternative to conventional cast-in-situ construction practices, driven by the increasing demand for rapid urbanization, improved construction quality, and reduced environmental impact. In this method, structural components such as columns, beams, and slabs are fabricated in controlled factory environments under strict quality assurance protocols and then transported to the construction site for assembly. This industrialized approach enables better dimensional accuracy, consistent material properties, and reduced dependency on on-site labor. Furthermore, prefabrication significantly minimizes construction waste, reduces noise and dust pollution, and enhances overall project efficiency, making it particularly suitable for large-scale and time-sensitive infrastructure projects. Despite these advantages, the structural performance and long-term reliability of prefabricated concrete systems are highly dependent on the efficiency of their connection mechanisms. Connections act as critical load-transfer interfaces between individual precast elements, ensuring continuity of forces and structural integrity under various loading conditions. Inadequate or poorly designed connections can compromise the global behavior of the structure, leading to issues such as reduced stiffness, premature failure, and vulnerability under extreme loading conditions, including seismic events. Therefore, the development of robust, reliable, and constructible connection systems is a key aspect of prefabricated construction technology. Among the various connection techniques, grouted sleeve connectors have been widely adopted due to their proven ability to provide effective reinforcement continuity between precast members. These systems consist of steel sleeves into which reinforcing bars are inserted and bonded using high-strength, non-shrink grout. The grout serves as a medium for stress transfer through adhesion, friction, and mechanical interlocking, while the surrounding steel sleeve provides confinement that enhances bond strength and prevents premature splitting of the grout. As a result, grouted sleeve connectors are capable of transmitting both tensile and compressive forces efficiently, making them suitable for critical structural applications. In recent years, half-grouted sleeve connectors (HGSCs) have gained considerable attention as a more economical and construction-friendly alternative to fully grouted systems. Unlike conventional sleeves, HGSCs utilize a hybrid load-transfer mechanism in which only a portion of the sleeve is filled with grout, while the remaining portion relies on mechanical anchorage of the reinforcement bar. This configuration reduces the volume of grout required, thereby lowering material costs and simplifying the grouting process. Additionally, HGSCs offer improved tolerance to construction inaccuracies, as the partially unbonded region allows for easier bar insertion and alignment during assembly. These features make HGSCs particularly attractive for precast construction, where speed and ease of installation are critical. However, the presence of both bonded and unbonded regions introduces complexity in the load transfer mechanism within HGSCs. The interaction between mechanical anchorage and grout bonding leads to non-uniform stress distribution along the embedment length, influencing the overall structural response. Factors such as embedment length, grout strength, sleeve geometry, and water-binder ratio significantly affect bond behavior, stiffness, and failure modes. Consequently, a comprehensive understanding of the structural performance, bond-slip characteristics, and failure mechanisms of HGSCs under various loading conditions is essential for their safe and efficient design.

This study aims to address these aspects by experimentally and numerically investigating the behavior of half-grouted sleeve connectors, with particular emphasis on load-displacement response, bond-slip behavior, crack patterns, and failure modes. The findings contribute to the development of design guidelines and practical recommendations for the implementation of HGSCs in modern prefabricated concrete structures.

II. OBJECTIVE

The main aim of the research is to critically assess the structural performance of half- grouted sleeve connectors (HGSC) applied in prefabricated column-footing connections that have been loaded both in the axial and the lateral direction. This experiment aims at determining the appropriateness of HGSCs as an efficient connection system in question of its strength, stiffness and general load-transfer processes under realistic conditions with regard to structural demand. One of the main points of the study is to research the bond behavior of reinforcing bars and grout that is key in the establishment of load transfer efficiency in the connector. In this respect, the research is expected to evolve an explicit comprehension of the bond-slip correlation, its variant phases, and the variables that contribute to bond strength and slip property.Another valuable goal is to identify and assess failure modes incurred in HGSCs. The paper discusses the different forms of failures like bar pull-out, bar fracture, and grout crushing, and aims at differentiating between ductile and brittle failure modes. These modes are critical in helping to establish that the connection is designed to be safe and ductile.The study also tries to determine how the important parameters affect the performance of HGSCs. Such parameters are:1) Water-binder ratio of the grout, which affects the strength, and quality of bond. 2)Anchorage (embedment) length of the reinforcement that determines the development of the bond. 3)Material properties of the grout, steel and sleeve, which determine the overall structural response. The analysis of these variables enables the study to identify the best design configurations that will improve the performance at a low cost. Besides the experimental researches, the paper also involves creation of a finite element model of ANSYS to model the behaviour of HGSCs. The purpose of such numerical method is to confirm experimental results, forecast patterns of distributions of stress, and give a more in-depth understanding of the internal mechanics of the connection. The experimental and numerical results can be compared to verify the reliability of simulation methods in designing and analyzing. In addition, the research assesses seismic suitability of HGSCs through their ductility, capacity of deformation, and energy dissipation of HGSCs under cyclic loading. This fact is especially significant in regard to their applicability in earthquake prone areas, where the connections should be able to maintain repeated loading with minimal loss of strength. Lastly, it is located on the overall findings that the study seeks to develop towards the successful application of half-grouted sleeve connectors in prefabricated concrete buildings. These recommendations are supposed to help engineers to optimise the design of connections in terms of safety, performance and constructability.

III. RESEARCH GAP

Prefabricated construction based on grouted sleeve connectors has been extensively implemented in prefabricated concrete construction because of the capacity of the bonding reinforcement continuity and proper transmission of loads among precast aspects. The available research is however mostly limited to fully grouted sleeve connectors and as such the behaviour of half-grouted sleeve connectors (HGSCs) is a relatively unexplored area. The HGSCs are also a hybrid in their load transfer mechanism compared to fully grouted system where only a portion of the sleeve is grouted and the rest is anchored by a mechanical connection of the reinforcement. This dual process brings in multi-complex interaction and non-uniform stress patterns along the embedded length and the structural response of HGSCs now becomes extremely different and unpredictable.

A major weakness of the literature available is the absence of large-scale experiments on HGSCs whose axial and lateral loading conditions were combined. In practice in structural applications, especially in column-footing and beam-column connections, connectors are seldom exposed to either axial forces or lateral forces only. This combined loading is particularly applicable in seismic areas where connections are required to survive simultaneous compressional and lateral forces acting on the connections cyclically. In the absence of such data, there is little that can be known about the performance and safety of HGSCs under realistic service and extreme conditions.

The other significant gap is associated with the effect of the important parameters on the HGSCs behavior. Modern design proposals and code standards are mostly empirical and were developed around fully grouted systems, and do not consider the special nature of partially grouted sleeves. The most important variables which could influence bond strength, stiffness and failure mechanisms include the embedment length of the reinforcement, the strength and the composition of the grout and the geometry and the dimensions of the sleeve. Nonetheless, there is little in the literature on systematic studies examining these parameters with regards to HGSCs, restricting the scope of optimizing design both in terms of performance and constructability.

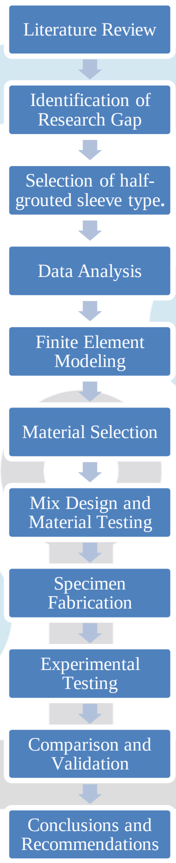
There is also insufficient knowledge on failure mechanisms in HGSCs. Although bar pull-out, grout crushing, and bar fracture have been determined as potential failure modes, too little information is available concerning the circumstances in which these modes can be found or can be changed into each other. It is important to differentiate between brittle failures, e.g. pull-out failure or grout crushing, on the one hand, and ductile failures, e.g. bar fracture, on the other hand, to be able to guarantee safe and predictable performance, especially in seismic applications.

Moreover, there are limited reliable numerical models that can well simulate the nonlinear behaviour of HGSCs. Due to the complex interaction of bond-slip, redistribution of stress and local damage that develop in the sleeve and grout under combined loading, existing finite element analyses can, in general, be unable to capture. Parametric studies, design optimization and the provision of predictive tools require validated numbers models to the engineers.

Collectively, the limitations indicate a definite necessity to have a combined experimental and analytical study of the structural, bond, and failure behavior of half-grouted sleeve connectors. A study like this would give holistic viewpoint on their functioning under realistic loading case, enhance the knowledge on the impacts of the key parameters, validate numerical modelling tools, and eventually offer excellent, evidence-based design guidelines on the reasonable and efficient utilization of HGSCs in prefabricated concrete construction.

IV. METHODOLOGY

The results of the experimental and analytical studies are integrated to come up with the insights on the load transfer mechanism and the behavior and failure of HGSCs. Recommendations are also provided based on the research findings on how the half-grouted sleeve connection should be designed with improved safety, efficiency, and applicability in prefabricated concrete structures.



V. NEED FOR PREFABRICATED CONSTRUCTION

Prefabricated construction has become a revolutionary practice in the construction industry today due to the growing pressures of delivering construction projects at a faster rate, being more efficient, and having a sustainable nature. This technique is characterized by the ex-situ manufacture of structural elements, i.e., columns, beams, walls, and slabs, in controlled factory conditions and their transportation and assemblage on the construction site. The increased urbanization, the development of infrastructure on a large scale and demand of cheap housing in most countries such as India has developed a strong urge to have new methods of construction that can help in the rapid completion of projects without compromising on the quality and safety.

Prefabricated construction has one of the greatest benefits that is a decrease in time spent on construction. The total length of the project can be dramatically reduced by keeping the parts of the structure being assembled off-site at the same time as the foundations and ready areas are prepared on-site. This method ensures that the property can be occupied faster and the money invested is recovered sooner but also reduced time spent on stalling due to weather conditions or other location related issues.

The other significant advantage is improved quality control. Manufacturing of structural elements under a structured factory environment guarantees equality in the nature of materials, uniformity in curing and compliance to the strict standards of quality. This level of accuracy decreases the chances of unreliability usually experienced during the traditional cast-in-situ construction, which enhances durability and performance of the building in the long term.

Prefabrication is also efficient in labour since it has minimised reliance on highly skilled workers in the construction site. Critical fabrication jobs are carried out in factory hence the on-site labor force is left to do assembly and supervision, thereby making construction management easier and saving labor expenses. This method also helps to optimize cost since there is minimal wastage of materials such as formwork, concrete and reinforcement as well as repetitions can be standardized in more than one part.

Prefabricated construction is more sustainable in nature, in terms of the environment. On-site operations also result in lower levels of noise, dust and construction materials whereas off-site manufacturing enables management of materials and wastes to be better handled. A cleaner environment can be aided by lower pollution in the sites, and minimal construction related disturbance especially in the congested cities. In addition, the approach increases the safety of the workers, since small numbers of risky operations are performed on the location, and the number of operations exposed to an unfavorable weather is reduced.

Although these are obvious benefits, coherence of structural connections is critical to the success of prefabricated construction. Prefabricated structures contrast with monolithic cast-in-situ systems; instead of using the mechanical or bonded connectors to transmit loads between two separate precast elements. The joints have to recreate the behavior of monolithic reinforced concrete joints to guarantee structural continuity, strength, stiffness and ductility. The nature of poorly developed or implemented connections may jeopardise the performance of prefabricated structures, lowering their resilience to service and extreme loads, such as seismic.

This means that prefabricated construction continues to be adopted and successful only when it is accompanied by an effective production and assembly system, as well as a strong and stable connection system. Connection technologies, including half-grouted sleeve connectors, should be developed and studied to reach the optimum of prefabricated systems, but in a manner that is safe, performing and enduring.

VI. TYPES OF REINFORCEMENT SPLICING METHODS

The main types are: The easiest technique is Lap Splice which is realised by overlaying 2 bars to some length. Although cost-effective, it has longer development lengths and causes reinforcement congestion, which prevents its use with high-strength concrete or high-diameter bars. Mechanical Coupler, this is the technique of fastening bars together with threaded couplers or sleeves which transmit mechanical forces. It offers good strength and smaller joints, yet, it is more expensive, in terms of machining, precision and professional set up. Grouted Sleeve Connection is a sleeve of steel stuffed with non-shrink, high-strength grout is used to bind the bars of neighboring elements. It has high load transfer capacity, high tolerance to misalignment and good bond properties than lap splices. Among them, the connection most frequently used is the grouted sleeve connection at precast column-to-footing and beam-column joints and in applications where they need to be installed quickly and have high loading capacity.

VII. LIMITATIONS OF CONVENTIONAL JOINTS

The traditional methods of reinforcement splicing, though commonly used in reinforced concrete construction, have a few inherent stressors especially in the prefabricated and modular prefabricated systems of construction, in which speed, precision and quality control is paramount in the successful implementation of the project at hand. These constraints may intervene with constructability and structural performance, which makes it important to find more efficient and reliable connection solutions.

One of the oldest methods used and most frequently is lap splicing, which involves a relatively long base of reinforcing bars to guarantee proper load transfer. The long length of this usually causes a growing cross sectional size of the member, especially in heavily reinforced areas like beam-column interfaces. This reinforcement congestion does not only make it difficult to place the bars, but also the correct compaction of concrete around the reinforcement that could create an empty area, honeycombing and other defects that would affect the structural integrity and durability of the connection. Furthermore, longer lap lengths take up excess space in precast elements, restricting the design, and reducing the amount of concrete needed.

The alternative of mechanical coupler offers a smaller size option that involves joining reinforcing bars on their ends removing long overlaps. Although this system may save on space and congestion of reinforcement, this system is usually costly, both in terms of material and installation. Mechanical couplers also require the bars to be perfectly aligned and threaded such that 100 percent of the load can be transferred. Such accuracy can be difficult in on-site applications particularly in large precast work where even slight misalignment or incorrect threading can decrease greatly the strength and stability of the bond. The sensitivity to workmanship may jeopardize the safety and may require extra supervision or remedial action.

Full-grouted sleeve connectors are structurally efficient, but have their own real-life difficulties despite the widespread use in precast construction. These systems will demand a big amount of high strength grout to guarantee that there is adequate bonding between the reinforcing bars and the sleeve. The procedure of the grouting requires strict quality control such as full filling of sleeve, care against air holes, and proper curing. Poor workmanship, grout mixing or curing may lead to partial bonding leading to load carrying capacity and the reliability of the connection. Moreover, increased grout volume increases the cost of the material and may complicate the handling and placement, particularly of the material where the space is limited or very congested.

Taken together, all these restrictions demonstrate the obvious necessity of an effective, cost-effective and construction-sensitive splicing system capable of retaining a high level of structural performance and ease of installation and quality control.

Half-grouted sleeve connectors (HGSCs) in this respect present a promising alternative. The ability of HGSCs to fill only part of the sleeve with grout and use mechanical anchorage to the rest of the sleeve allows the prevention of excessive grout volume whilst maintaining bond strength and confinement. This structure helps eliminate congestion at reinforcing and simplifies alignment and installation, as well as minimizes the need to have highly skilled operating personnel to fix the grouting. Moreover, the simplified construction process will improve the overall quality control and minimize the threat of defects to achieve more predictable structural performance. Such benefits precondition the HGSCs being especially appropriate to the contemporary prefabricated and modular structures, where the speed of construction, economic feasibility, and structural behaviour are critical.

VIII. MATERIAL USED

The main resources of the preparation of the specimen include: concrete, steel reinforcement, grout and steel sleeve. All materials used were chosen according to their mechanical, availability and prefabricated connection properties.

A. Reinforcement Properties

The reinforcement was done with high yield strength deformed bars (HYSD) of Fe500 grade. The connection and structural members were made of bars with a diameter of 12 mm and 16 mm.
Tensile tests were used to measure the mechanical properties in a Universal Testing Machine (UTM).
activities.

Name of material	Yield strength/MPa	Tensile strength/MPa	Modulus of elasticity/MPa	Poisson's ratio
Rebar	479.1	656.8	2.0×10^5	0.3
Sleeve	448.6	624	2.1×10^5	0.3

B. Grout Material and Additives

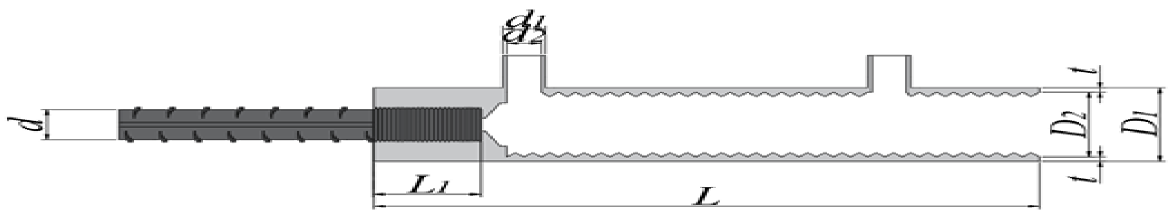
The half-grouted sleeve connectors (HGSCs) were constructed in this work with the aid of high-strength, non-shrink cementitious grout, that is, Fosroc Conbextra GP2 (or SikaGrout 214). The grout was chosen because it has a very good flowability, high վաղ early strength and non-shrink qualities that are required to ensure that the sleeve is properly bonded and filled to the last. These properties will guarantee effective transfer of loads between the reinforcement bar and the steel sleeve.
The grout was prepared as per the instructions of the manufacturer keeping the water-to-powder ratio as per the recommendation to attain the best of workability and strength. The correct mixing operations were observed to create a homogenous and non-lump consistency and the grout was thoroughly poured into the sleeve to avoid the trapping of air. The grout was non-shrinking, and this reduced the volumetric changes that might occur during the curing process and ensured good contact and confinement between the steel bar and sleeve.
In order to ascertain the mechanical performance of the grout, compressive strength tests with respect to various curing ages were performed on normal cube specimens. The findings are as in Table below.

Curing Age (Days)	Compressive Strength (MPa)
7 Days	42 – 48
14 Days	50 – 55
28 Days	60 – 70

The findings show that the grout was suitable for structural applications because it attained high compressive strength early on and continued to gain strength over time. The overall performance, stiffness, and durability of the half-grouted sleeve connections were greatly enhanced by the grout's high strength and strong bonding properties.

C. Steel Sleeve Dimensions and Properties

To provide mechanical confinement, the half-grouted sleeve was made of ductile cast iron or mild steel. The sleeve had two ends: one was plain to be filled with grout and the other was threaded for mechanical anchorage.
The sleeve had a yield strength of 250 MPa and a tensile strength of about 400 MPa. During filling, a hole was made for grouting and air escape.



IX. NUMERICAL ANALYSIS AND SIMULATION

The structural behavior of half-grouted sleeve connectors under various loading scenarios is simulated using finite element modeling (FEM). It aids in comprehending bond-slip behavior, deformation patterns, and internal stress distribution—all of which are challenging to observe experimentally. In order to validate the experimental results and conduct a parametric study on important influencing factors like embedment length, grout strength, and sleeve geometry, numerical analysis was carried out using ANSYS Workbench.

The model mimics the experimental configuration of a column-footing joint under axial and cyclic loads, connected by a half-grouted sleeve.

A. Model Development in ANSYS

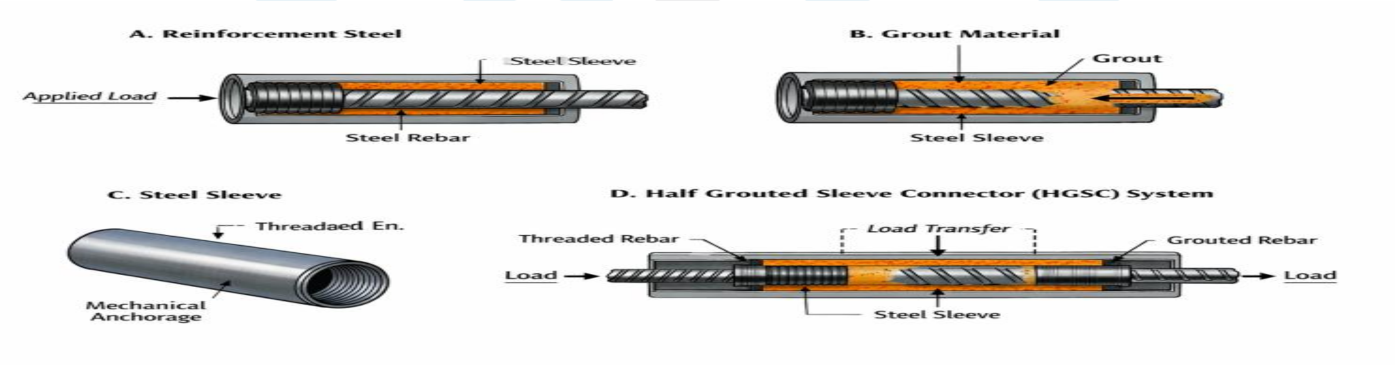
SolidWorks was used to create the connection's 3D model, which was then imported into ANSYS for meshing and analysis. Among the geometry were:
An internal-threaded steel sleeve
A reinforcement bar that extends into the column portion and is embedded into the sleeve

The area of grout that fills the gap between the sleeve and rebar, and
The footing and column are represented by concrete blocks.

To precisely capture local stress variations, a fine hexahedral mesh was used in the grout and sleeve zones. Refining until stress values changed by less than 3% guaranteed mesh convergence.

B. Element Type and Boundary Conditions

The element types utilized were as follows:
SOLID186 (in ANSYS) for grout and concrete,
The steel sleeve's components are SOLID187.
Boundary Conditions:
The footing's bottom was fixed in every direction.
To replicate tensile loading, axial displacement or load was applied at the free end of the rebar.
Wherever possible, symmetry conditions were applied to minimize computational expenses.



X. LOADING ARRANGEMENTS (AXIAL, LATERAL)

There were two kinds of loading used:
Axial loading: To assess the failure mode and ultimate bond strength. Until failure, a load is applied at a rate of 1 kN/s.
Lateral Loading: Applying a load horizontally at the top of the column to simulate seismic action.

A. Analytical Modeling Using ANSYS

MATERIAL MODELS:

Concrete exhibits nonlinear cracking and crushing behavior.
Grout is a high-strength elastic-plastic material, while steel undergoes bilinear kinematic hardening. Boundary conditions were used to simulate an axially applied load at the top of the column and a fixed footing.Results were extracted and compared with experimental data, including stress contours, strain distribution, load-slip curves, and failure zones.Test and simulation results were found to be closely correlated (within ±10%) during validation.

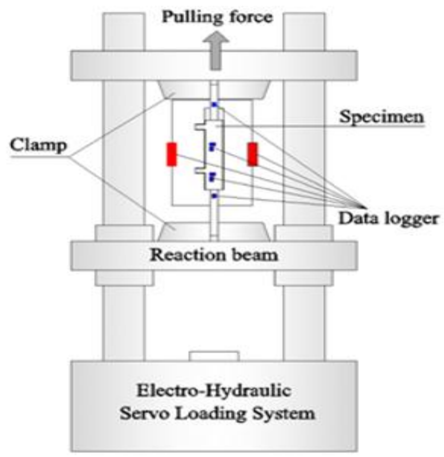
ANALYTICAL FINDINGS

The results of the numerical simulation agreed with the findings of the experiment, indicating that:
Grout confinement and mechanical interlock are the main ways that bond stress is transferred. Adequate embedment and balanced grout strength lead to optimal performance. The beginning of failure is controlled by stress concentrations close to the sleeve mouth. The behavior of HGSCs under various loading scenarios is accurately predicted by the suggested finite element model. In order to ensure strength and ductility in both seismic and non-seismic zones, these findings support the use of half-grouted sleeve connectors in prefabricated concrete structures.

XI. EXPERIMENTAL METHOD

A. Testing Procedure

The tests were carried out using a hydraulic loading frame of a capacity of 2000 kN.
The tests were carried out under monotonic axial tension and cyclic loading conditions to simulate real-field behavior.
Axial Load Test: The axial load was applied gradually by a hydraulic actuator at a constant rate of 1 kN/s until failure.
Cyclic Load Test: The repeated loading and unloading cycles were applied to assess ductility and energy absorption.
Displacement Measurement: LVDT measured the displacement between the column and footing. Strain gauges measured the strain distribution of the reinforcement bars and sleeve. The measurements were taken by a data acquisition system connected to the sensors.



B. Observations during Testing

During the tests, the following observations were made:
The specimens were found to be elastic at first, showing linear behavior. Small cracks were observed near the grouted area at approximately 70-80% of the ultimate load. Further increase in the applied load resulted in visible slip between the bar and the grout, followed by cracking and crushing of the grout near the sleeve end. Failure could be either by pull-out, fracture of the bars, or debonding, depending on the anchorage length.
The specimens with longer anchorage length of 6d or 8d showed higher capacity to withstand the applied load compared to those with shorter anchorage length.

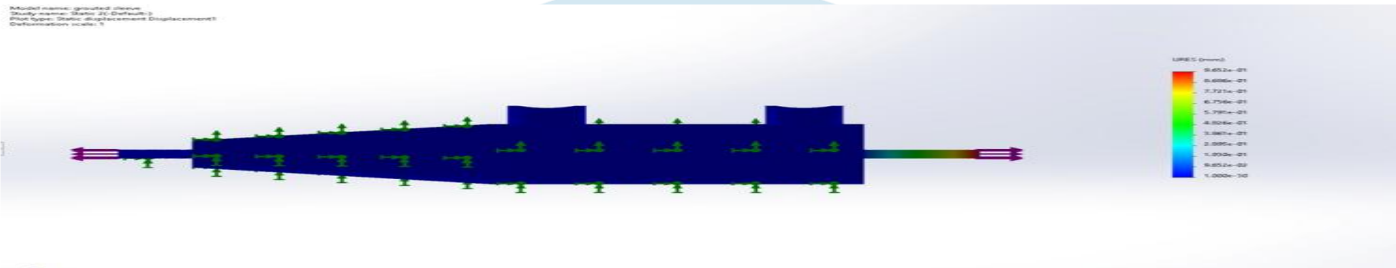
XII. Experimental Results

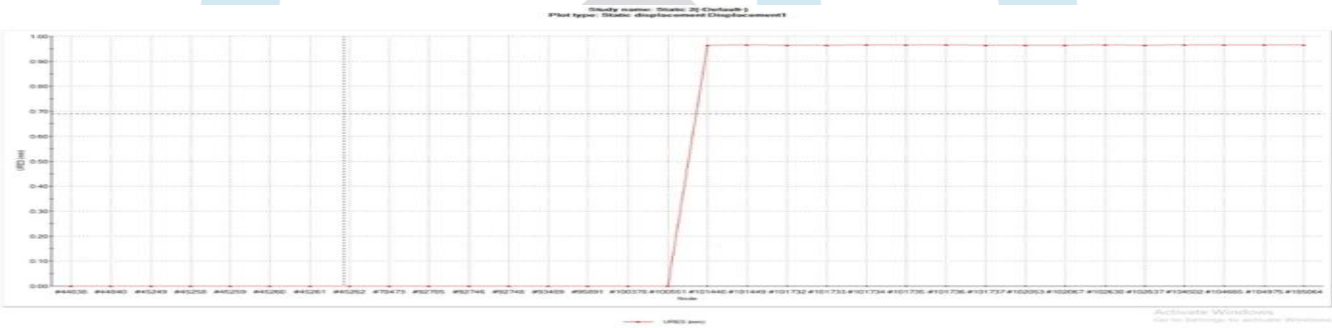
The experimental investigation findings were summarized in the form of load, displacement, strain and failure mode of all the specimens. The key parameters involved were ultimate load, bond strength, slip behavior and energy dissipation.
The load-displacement curve of all the tested specimens gives significant details on the stiffness, strength and ductility nature of half-grouted sleeve connectors (HGSCs). The curves repeatedly showed three unique behavioral phases, which are an initial linear elastic phase, a nonlinear transition period, and a post-peak softening phase.
At the beginning linear section, the displacement was proportional to the load i.e. there was effective composite action between the reinforcement, grout and sleeve. This is the stage of the elastic rigidity of the system since there will be no major cracking or degradation of bonds. Lower water-binder ratios (0.25) in specimens showed significantly steeper gradients in this area, which is a sign of greater initial stiffness because of denser and stronger grout containing better interfacial bonding.
With further loading, the response was observed to enter a nonlinear regime above the yield point, with micro-cracking starting in the grout as well as at the interface between the grout and steel. This phase is marked by the development of gradual stiffness reduction since redistribution of bond stress takes place along the embedment length. The shift in the behaviour between the linear and the nonlinear behaviour was also less pronounced in specimens of 6d and 8d embedment length implying that the stress distribution was more appropriate and the localised damage was delayed in the specimens.
Embedment length was a very important factor affecting the ultimate load capacity. The 6d and 8d specimens with anchorage length had a peak loading of about 20-30 percent greater than that of the 4d specimens. This can be explained by the greater amount of contact area that the bonds have to interact and this gives them an opportunity to transmit the stress more efficiently and low chances of premature failure of bonds. But the marginal utility of 6d versus 8d suggests that 6d can be a close to optimal design.

All the specimens had a gradually decreasing branch to the peak load, which suggested ductile behavior, and not a brittle catastrophe. Such softening after the peak was more pronounced and steady in the specimens that had longer embedment length and high quality grout that enabled gradual bond degradation and redistribution of stresses instead of sudden pullout. Conversely, specimens of shorter embedment (4d) exhibited a more acute reduction in load, which indicated the decrease in ductility and predisposition to bond-slip failure.

The energy that was absorbed under the load-displacement curve was considerably higher when the specimens were of greater grout strength and had been compacted appropriately. It means it is tougher and can resist deformation without reduction in load carrying capacity. Improved energy consumption is of special use in the case of applications that are prone to dynamic or seismic loading and in which repeated energy dissipation is necessary.

In general, the results of the load-displacement behavior confirm that the embedment length and the quality of grout are important parameters by which structural performance of HGSCs is determined. Optimal ratios of these parameters result in increased stiffness, increased strength, increased ductility and increased energy dissipating capacity.



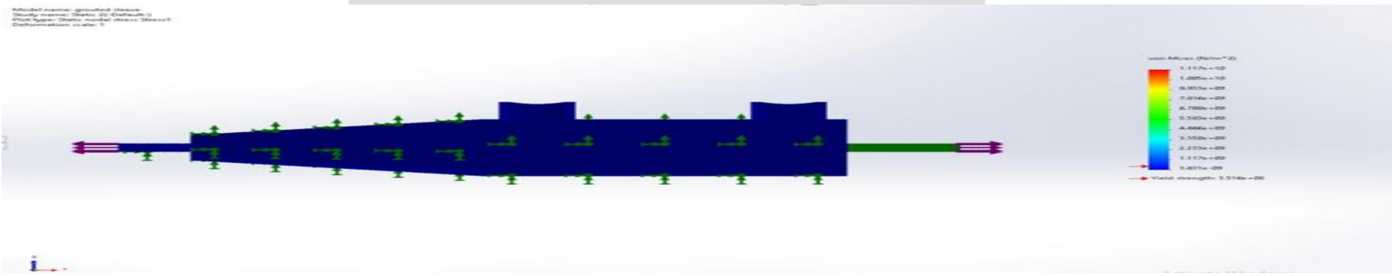


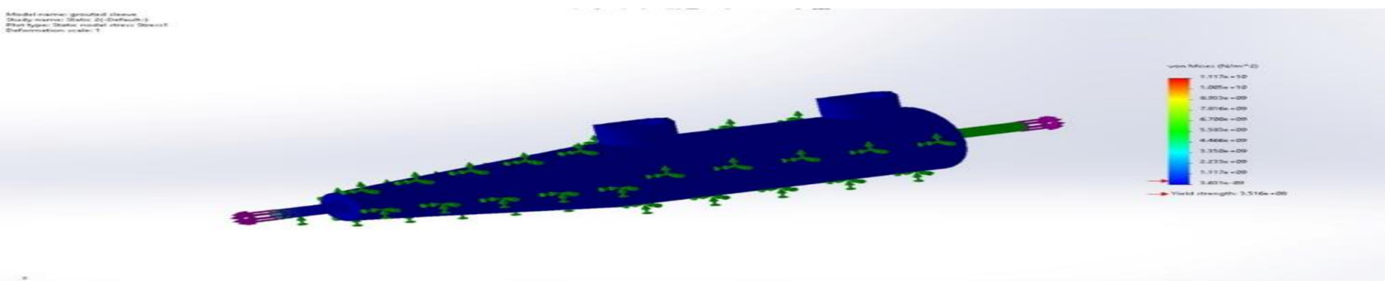
A. Stress–Strain Relationships

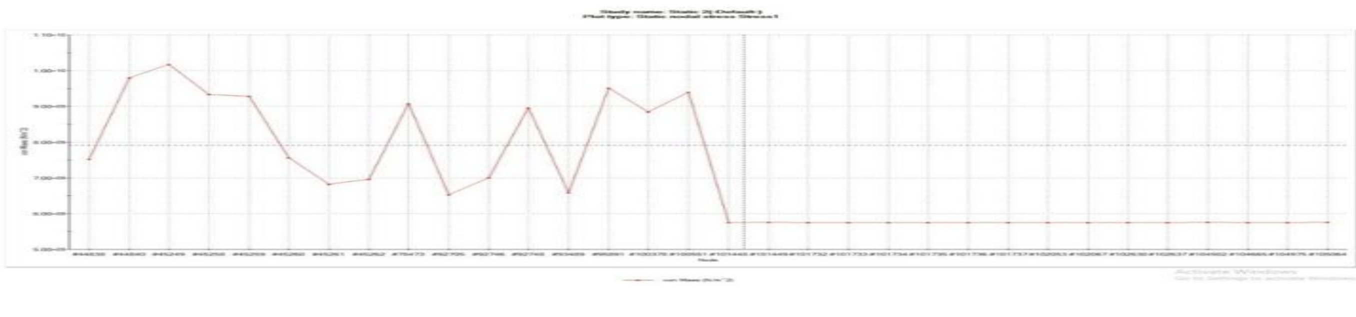
The results of the strain gauge readings to obtain the stress-strain curves indicated:

Elasticity up to strain of 0.002.

Before ultimate failure, yielding took place in the reinforcement around the threaded section. In other instances, the crushing of the grout started prematurely, which resulted in redistribution of stresses in the sleeve. The findings proved that there was a good load transfer efficiency of steel, grout and sleeve up to ultimate failure.







Crack Patterns and Failure Modes

The crack patterns and failure modes are investigated as a significant source of insight in the internal stress distribution and bond performance of half-grouted sleeve connectors (HGSCs). The measured crack behavior and the failure modes is clearly noted to be effective of the embedment length, the quality of grout and the confinement in the sleeve.

1. Rebar Pull-out Failure
Rebar pull-out was mainly noticed in specimens that had less anchorage lengths (4d). This failure mode was as a result of the lack of development of the bond between the reinforcement and the surrounding grout. When the applied force was raised, the interfacial resistance was not enough to support the bond stress and progressively the bar slipped in the sleeve. This kind of failure is marked by a comparatively abrupt loss of load bearing ability as well as restricted ductility, which implies brittle reaction. The fact that there was no substantial yielding in the reinforcement is also a clear indication that the strength of the bond was insufficient to generate the entire tensile strength of the bar.

2. The rebars fail in ductile manner (Rebar Fracture).
Failure in specimens having higher embedment length (6d-8d) was caused by fracture of the reinforcing bar. This implies that the cementing of the grout to the reinforcement was good to develop tensile power of the steel completely. This is a good performance in the structural design because it indicates effective transfer of stress and ductile behavior. Before the fracture, the extension and elongation of the bar were evident, and the propagation of cracks in the surrounding grout was constant. This mode guarantees a warning of impending failure and a greater capacity of dissipating energy.

3. Sleeve Deformation and Grout Crushing.The grout crushing and deformation of the sleeve were localized around the sleeve mouth that is characterized by the highest level of stress concentration. The combination of radial and longitudinal stresses is caused by the transfer of the load between the bar and sleeve in this region. Minor outward deformation of the sleeve was observed in other instances, which is a sign of the internal pressure built up by the confined grout. These local failures were not always connected with the instant collapse but were the factors in the stiffness degradation and gradual harm.

4. Crack Patterns
The patterns of crack which were found in the specimens were basically radial and circumferential on the sleeve. The cracks were radial and they were due to the reinforcement, and the circumferential cracks occurred because of hoop stresses in the grout. These trends are consistent with the fact that tensile loads are satisfactorily passed on in the grout medium and opposed by the sleeve restraint.
Better confined specimens with lower water-binder ratios had finer and more homogeneously distributed cracks, which implied control of stress distribution. Conversely, the specimens that had a higher ratio of water-binder exhibited broader and more discontinuous patterns of the crack which were indicative of lesser grout strength as well as of lesser mqwmt to tensile stresses.

5. The effect of the ratio of water and binder.
The water-binder (w/b) ratio showed a great influence on the formation of the crack. Increased w/b ratios led to greater porosity and lower grout strengths, an earlier onset of cracks and a greater crack opening. These samples were found to have less crack propagation resistance and bond efficiency. On the other hand, reduced w/b ratios resulted in a denser grout having better mechanical properties thus leading to delayed cracking, reduced crack widths and increased durability.

Overall Interpretation
The crack patterns and failure modes observed clearly indicate that an appropriate embedment length, good quality of grout and effective confinement are very necessary to attain ductile and reliable performance of HGSCs. The consideration of such factors can promote the failure mode to be brittle pull-out to ductile bar fracture that is the desired failure behavior in structural applications.

B. Bond–Slip Behavior

One of the parameters that control the performance of half-grouted sleeve connectors (HGSCs) is the bond-slip relationship between the reinforcing bar and the grout. The experimental observations showed that there was a three-stage response of the bond slip that was the progressive interaction and the eventual wear and tear of the bond mechanism as the load increased.
Elastic Stage
At the first stage, bond-slip curve was shown to have a linear relationship between bond stress and slip. This does show great adhesiveness and mechanical interlocking of the reinforcement and the surrounding grout. At this point, the amount of slip is insignificant and can be actually ignored since the corresponding load is actually transduced by way of chemical bonding and frictional resistance at the interface. There is no observable cracking or damage done to the grout and the system is elastic and stiff.

Yield (Nonlinear) Stage
The response at increasing loads changes to the nonlinear (yield) stage, and micro-cracking commences to occur in the grout matrix and the grout-steel interface. These micro-cracks minimize the rigidity of the bond causing the gradually escalating slip-off minus corresponding escalation of bond stress. Mechanical interlocking and friction take over as the primary load-resisting mechanisms and the role of chemical adhesion decreases. This phase is the reflection of bond weakening, yet the bond retains its load carrying capacity.

Post-Peak Stage

Once the peak bond stress is attained, the bond-slip curve enters the post-peak region which entails a very steep increase in the slip with a decrease in the bond stress. This action signifies that a lot of interfacial resistance has been lost through a huge amount of cracking, grout crushing and mechanical interlock breakdown. This step causes bar pull-out failure in specimens whose confinement is not enough, or whose embedment length is too short which in many cases is in a rather brittle fashion. The post-peak response can also be of a more gradual nature in well-confined systems, which means that there is some residual frictional resistance.

Embedment Length Influence The length of the embedment influences the strength and weight of the connection.<|human|>Embedment Length Influence The embedding length determines the weight and strength of the connection.

There was a strong influence on bond performance by the embedment length. Specimens that had 6d embedment length had the best bond strength, which means that there was optimal stress distribution and effective utilization of bonded interface. Embedment length (e.g. 4d) was too short to develop full bond capacity, the bond capacity would mature early and cause early slipping and low strength. Though there was an increase in performance with increased embedment but the difference between 8d and above was quite insignificant implying that 6d is a practical and efficient design value.

Binder Ratio Water Influence.

The water-binder (w/b) ratio had a great effect on the bond-slip reaction. The specimen that had a low w/b ratio (0.25) had a better bond strength, scarcer slip and steeper initial slope which is a sign of stiffer and more powerful bonding. This is explained by the denser microstructure, and mechanical properties of the grout are better.

Conversely, the greater w/b ratios resulted in greater porosity and, therefore, reduced interfacial bonding, which caused the excessive slip and reduced bond strength. These specimens exhibited a previous shift to the nonlinear stage and more abrupt post-peak response indicating a lower level of durability and reliability.

C. Experimental Outcomes

The findings of the experiment indicate the relevance of the length of anchorage, grout properties and sleeve geometry in connection performance.

Key findings include:

The strength and ductility are very much influenced by anchorage. Further embedment of more than 6d is marginally beneficial.

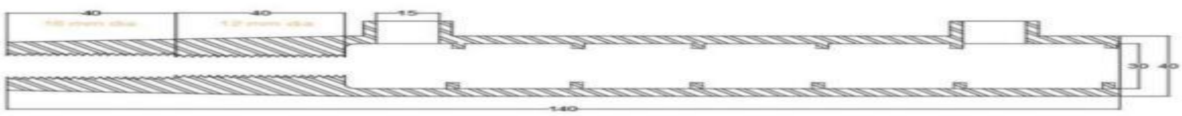
The strength of grout is significant in the transfer of stress. Reduction in water decreases softening and adhesiveness. Misalignment and eccentricity decrease the effective bond strength and they lead to an uneven stress distribution. The load-slip behavior showed that there was the goodness of ductility, which is appropriate to prefabricated construction under seismic loading. Mostly failure was out of the sleeve in well-bonded specimens and this is evidence of sufficient connection design. In general, half-grouted sleeve connectors were characterised by safe and efficient performance in comparison with monolithic cast-in-situ joints.

XIII. PARAMETRIC STUDY

A comprehensive parametric study, once the validation was done, was conducted to have insight into how important parameters affect the connection behavior.

Three embedment lengths (4d, 6d and 8d) were tested.

Findings revealed that an extension of embedment length enhanced significantly ultimate load and bond strength to a depth of 6d. In addition to this, the rise was low, which means that there was an optimum length of anchorage of 6d. The strengths of the grout (40, 60 and 80 Mpa) were modeled.An increase in grout strength increased the stiffness and minimized the slipping at the sleeve-bar interface. But very high grout strength also resulted in brittle failure, and it was found that sleeve wall thickness (6 mm) and sleeve wall length (6 mm) are the most balanced to ensure confinement, reduce weight, and reduce cost. Internal geometry tapered sleeves have a more uniform distribution of stresses and slow local cracking; therefore, they are better suited to practical use.



XIV. Comparative Analysis of Results

A comparison between experimental results, analytical simulations, and literature data was carried out:

Parameter	Experimental Value	Analytical (ANSYS)	Deviation (%)
Ultimate Load (kN)	140	135	3.6
Maximum Slip (mm)	1.8	1.9	5.5
Bond Stress (MPa)	12.5	11.9	4.8

The variation between experimental and numerical results was within ±5%, indicating good model accuracy. Compared to previous studies, the tested HGSC specimens demonstrated better ductility and higher load-bearing capacity, validating their suitability for use in prefabricated RC structures.

XV. Design Recommendations

Embedment Length The minimum embedment length of 6 times the bar diameter (6d) is suggested so that the anchorage is sufficient and satisfactory bond strength can be achieved between reinforcement and grout. This length has been discovered to bring the tensile strength of the reinforcing bar into service and yet the bond does not fail prematurely. Embedment below this extent may cause bond-slip failure, whereas beyond this extent, the benefit of embedment is diminishing and it may not be cost effective. So, the use of 6d as a design principle guarantees safety and material efficiency. Grout Properties The grout choice is vital towards the attainment of dependable performance of half-grouted sleeve connectors. High-strength grout of compressive strength of about 60-80 MPA and non-shrink is to be used. The water-binder ratio to be used should be low in order to increase the density, decrease porosity and enhance bond characteristics. One thing that reduced the bond strength is the presence of micro-voids and gaps between the grout and reinforcement, which is prevented by non-shrink properties. Grout should also be properly cured in order to attain the required mechanical properties and durability in the long term. Sleeve Geometry Confinement and stress transfer is very dependent on the geometry of the sleeve. Internal ribs/grooves should be provided in a tapered form or profile to achieve the mechanical interlocking between the grout and sleeve, and hence improve the performance of bonding. Sufficient sleeve wall thickness should also be done to counter radial stresses occurring during the peak loading condition and to counter cracking or splitting of the sleeve. Optimized sleeve geometry is known to enhance performance of structure as well as to play a role in evenly distributing stresses along the embedded length. Quality Control Appropriate construction methods are necessary to accomplish the desired functioning of HGSCs. Complete and void-free filling of grout dkhl the sleeve is imperative in nature. Poor grouting may result in nooks and crannies that greatly decrease the bond strength, thus making it easy to fail early. The methods that should be used to ensure that one has filled it correctly should include the use of controlled grout injection, flowable grout, visual inspection or non-destructive testing. The quality control in the course of installation is the direct effect of the quality of the connection. Seismic Application The location of HGSCs is to be taken into serious consideration in seismic areas. It is suggested that such connectors should be installed outside the main folds of plastics that will undergo considerable deformations that cannot be elastic in case of an earthquake. Placing the connectors in areas other than these is useful in avoiding early damages or degradation of the connectors under the cyclic loads. When carefully described, HGSCs will be able to add to the total structural ductility and dissipation of energy, but they need to be located in line with the seismic design principles to be resilient. Testing and Validation On-site tests and verification should be conducted in order to guarantee the reliability of connections in real-world situations. Tensile tests or pull-out tests on sample connections are encouraged to ensure that the installed connectors have the necessary strength and deformation standards. These tests give assurance on the quality of construction and would allow detection of any problems before actual implementation. Periodical sampling and testing are also helpful in adhering to design specifications and standards. Overall Implication All these recommendations give a viable guideline on the safe and efficient use of half-grouted sleeve connectors in precast concrete structures. With proper consideration of embedment length, material characteristics, geometrical set up, construction procedures and seismic detailing, engineers are able to ascertain optimum structural functioning, strength and constructability.

XVI. Major Findings

Load-Carrying Capacity

The half-grouted sleeve connectors (HGSCs) had enough load-bearing capacity when subjected to both the axial and lateral loading conditions, which justified their structural soundness. The findings make it obvious that the more compressive the strength of the grout it becomes, the higher the stiffness and the final load bearing capacity of the connection. Also, the longer the embedment, the better the distribution of the stress along the reinforcement and the less stress concentration at the end of the load. The result is increased tensile and shear strength hence the connectors can be used in structural applications that are demanding.

Bond Behavior

The interaction of bond between reinforcing bar and the surrounding grout is very important in the overall performance of HGSCs. It was noted that the better the confinement in the sleeve is due to proper sleeve geometry and grout density the stronger the bond is. The bond-slip curve shows an initial linear elastic trend meaning that there is a success in the transfer of the load. With increasing loading, nonlinear behavior occurs because of the micro-cracking and progressive debonding, and finally causes failure. The significance of this transition is the need to have a good interfacial adhesion to postpone slip and improve performance.

Failure Modes

Two major failure mechanisms were determined:

Bar Fracture (Ductile Failure): It takes place when the adhesion between the grout and reinforcement is such that tensile strength of the steel bar is fully utilized. It is the mode of failure that is desired because it implies the efficiency of load transfer and structural ductility.

Bond Slip Failure (Brittle Failure): This failure mode is caused by the incompetence of grouting or weak compaction that weakens the bond and the bar comes out of the sleeve before it reaches the yield strength.
These results highlight that grout richness, compaction and curing should be handled well to be confident of reliable and ductile behavior.
Effect of Parameters
The research determined the major parameters that affect performance:
Embedment Length: Embedment length of about 6 times the diameter of the bar (6d) was found to be effective enough to achieve a full bond strength and achieve anchorage without working too much material.
Grout Thickness: When grout is too thick, it causes less confinement pressure in the sleeve, which compromises the performance of bond. On the other hand, a finer and well-confined layer of grout enhances the performance of transfer of stress.
Material Properties: An increase in the grout strength and the mix design will increase bond and the overall connector performance.
These knowledge can be applied in efficient and safety design optimization.
Numerical Validation
ANSYS results visualized the strong correlation with experimental findings through the use of finite element modeling and ultimate deformations and ultimate load that had deviations that were less than 10%. This confirms the accurateness of the numerical model in predicting the behavior of HGSC. The figure of the stress contour plots were useful in showing how a diagonal compression strut (approximately 45deg) was formed, which is a typical loading transfer mechanism in a confined structure. This contract takes into account the fact that the numerical simulation is reliable in terms of parametric investigation and the design optimization.
Ductile and Dissipation of Energy.
In cyclic loading conditions, HGSCs showed constant hysteretic behaviour with a good energy dissipation capacity. This implies that they can undergo numerous loading and unloading processes without major loss in their strength. The connectors were also sufficiently ductile so that they could deform without failure. The traits are mainly significant to buildings located in seismic areas where the absorption and deformation properties of the buildings are critical to avoiding collapse.
Practical Relevance
In the construction aspect, HGSCs provide a number of benefits over the conventional reinforcement splicing techniques including lap splicing and welding. They are easy to install, less dependent on skilled labor and less time is used in construction. Moreover, the fabrication under the control of the factory guarantees uniform quality and the chances of making mistakes on-site are quite low. They are convenient and can be trusted to perform well in the new construction particularly the precast and modular systems.

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