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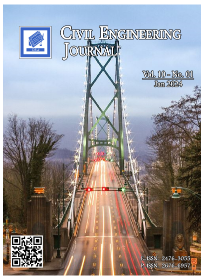

Lateral Displacement Behavior of IBS Precast Concrete Elements Reinforced with Dual System

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Abstract

Throughout history, the construction industry has been a significant contributor to construction waste, presenting an ongoing challenge in efficiently managing this waste to mitigate environmental pollution. The Industrialized Building System (IBS) stands out as a construction approach that utilizes prefabricated components made from various waste materials, implemented with machinery and formwork, leading to minimal waste production. The potential failure of IBS blockwork columns under lateral loads is a significant concern, and the deformation of these columns is crucial in assessing overall structural performance against lateral forces. This study focuses on examining the deformation and flexibility of components in IBS blockwork columns when subjected to lateral loads. Using Finite Element Modeling (FEM), a 1:5 scale prototype model of the dual-reinforced system IBS Block Work Column is analyzed. The IBS Block Work Column, comprising four prefabricated components assembled in the form of a crucifix plan to enhance lateral stability, is subjected to FEM analysis and experimental investigations. The study aims to explore the impact of four different shapes of reinforcement on deformation resistance. The findings suggest that employing a dual-reinforced system in the IBS Block Work Column enhances its resistance to lateral loads compared to a column with conventional reinforcement. Moreover, the assembled IBS Block Work Column exhibits greater stiffness than a single prefabricated component when subjected to lateral loads.

Keywords: Industrialized Building System; Block Work Column; Conventional Reinforcement; Finite Element Modeling.

1. Introduction

Over the years, the construction industry has continuously been a significant contributor to construction waste, presenting an ongoing challenge in effectively addressing and mitigating its environmental impact [1, 2]. Moreover, the construction sector plays a vital role in the advancement of nations, whether they are in the process of development or already established on a global scale. Research has substantiated that this industry is resource-intensive, utilizing up to 60% of the Earth's extracted raw materials [2–4]. In general, the IBS can be defined as any building components that

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are mass-produced, either in a factory or on-site. All the mass-produced components of the building are designed in accordance with specifications and standardized shapes and dimensions [2, 5]. The introduction of the Industrialized Building System (IBS) took place in various locations globally, particularly in Malaysia, during the early 1960s. In subsequent years, many countries have invested substantial efforts in promoting this technologically advanced construction method, IBS, as a way to enhance traditional, labour-intensive construction practices. The objective of this initiative is to empower countries to produce rapid and high-quality products capable of competing effectively in the global market. However, the widespread adoption of IBS in many countries encounters challenges, largely arising from past experiences of subpar quality in IBS construction projects. [1, 6, 7]. The Industrialized Building System (IBS) has been implemented in the construction sector to address numerous challenges present in the fragmented construction industry, aiming to optimize production output, reduce labor forces, and enhance overall quality. Various types of IBS systems exist, encompassing precast concrete frame systems, box systems, steel formwork systems, systems of steel frame systems, prefabricated timber systems, and block work systems [3, 8].

The United States and Japan boast the world's largest construction industries and have well-established global strategies [8]. The ability of construction industries to enter the global market relies on three fundamental factors: firstly, having technological advantages linked to robust construction technologies; secondly, deploying advanced management systems for activities such as scheduling, material tracking, and subcontractor organization; and thirdly, possessing the financial capacity to secure project financing from international financiers [1, 8–10]. Technology plays a pivotal role in propelling the construction industry to attain international standards, enabling construction companies to achieve sustained profitability and ensure balanced growth in the future [11]. The study encompasses an analysis of four countries: the United States, the United Kingdom, Australia, and Malaysia. It is noteworthy that off-site manufacturing in the United States was initially introduced by [4, 8, 12].

Lachimpadi et al. [3] examine the production of construction waste in the construction of high-rise buildings, employing three distinct construction methods: the Conventional Construction Building System (Category I), the Mixed System (Category II), and the Industrialized Building System (IBS, Category III). Their investigation includes the evaluation of both mineral and non-mineral waste generated for each construction category and the assessment of various waste management components [4]. Moreover, their research involves calculations to ascertain construction waste usage efficiency (CWUE) and scrutinize rates of waste reuse and recycling, with the goal of identifying the most effective practices. Remarkably, the IBS construction method (Category III) stands out as the most resource-efficient, showcasing the lowest waste generation rate (WGR) at 0.016 tons of construction waste per square meter of floor space. This is in contrast to the Mixed System (Category II) at 0.030 tons/m² and the Conventional Construction (Category I) at 0.048 tons/m² [3, 13]. The results of the study also highlight the impressive construction waste usage efficiency (CWUE) observed in Category III (IBS) at 94.1%, with only 5.9% of the total construction waste in this category being disposed of in landfills. It is noteworthy that the Construction Industry Development Board (CIDB) of Malaysia has recognized these significant findings [3]. The major portion of the mineral component, constituting 75%, was predominantly composed of sand and soil. On average, concrete and aggregate made up 14% of this component. Bricks and blocks collectively represented 2% of the entire fraction, while tiles and scrap metal each contributed an average of 1%. Conversely, in terms of the non-mineral fractions illustrated in Figure 1, packaging products accounted for the highest recorded proportion.

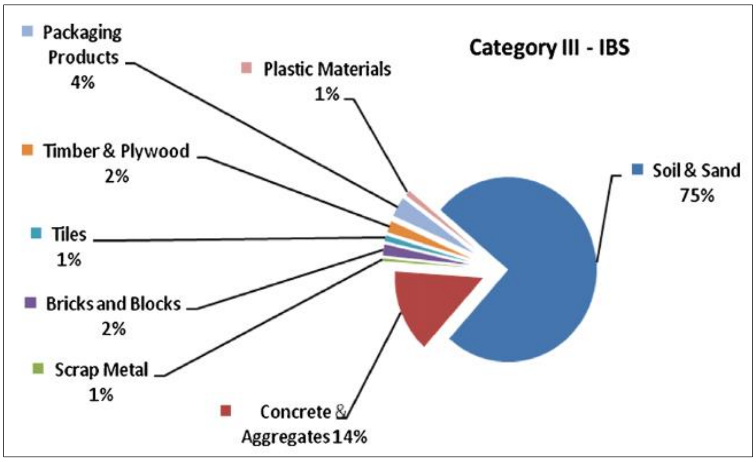


Figure 1. The mineral and non-mineral constituents for the IBS method (Category III) are represented as the mean percentage (%) of the total generated construction waste [3]

The determination of whether to repurpose, recycle, or dispose of construction waste varied across the three categories. Table 1 provides an overview of the total construction waste generated in IBS, categorized and separated based on its intended use and disposal [3].

Table 1. The overall construction waste generated and its classification according to its intended use and disposal for Categories III - IBS [3]

Category	Site	Total construction waste generated		Segregation of construction waste – (Tons)					
				Reused at site		Recycled		Disposed at landfills	
		(Tons)	%	(Tons)	%	(Tons)	%	(Tons)	%
III – Industrialized Building System (IBS)	Site 6	1730	100	1543.2	89.2	86.5	5	100.3	5.8
	Site 7	600	100	552	92	21	3.5	27	4.5
	Site 8	1130	100	932.2	82.5	113	10	84.8	7.5

The concept of IBS is employed to denote the prefabrication and industrialization of construction processes in East Asia, especially Malaysia and Middle Eastern countries [2, 4, 14]. This term was introduced to deviate from the conventional framework of prefabricated systems [6, 15]. IBS is introduced as an approach that offers improved productivity, quality, and safety [16–18].

However, it is important to highlight that the terminology employed in construction industrialization is frequently unclear and used interchangeably with other terms. The precise definitions of these terms heavily depend on the user's experience and comprehension, and they may differ from one country to another [4, 19].

A more expansive view of IBS entails departing from traditional perspectives, restructuring human capital development, cultivating enhanced collaboration and trust, and advocating for transparency and integrity. It is widely agreed, however, that the drive toward the industrialization of the construction industry is a worldwide endeavor, not limited to a single local or isolated initiative. The definitions and categorizations must evolve to align with global perspectives and comprehension [4]. This necessitates a re-evaluation of terms such as offsite, prefabrication, offsite construction, modern methods of construction, offsite production, offsite manufacturing, and pre-assembly. Such a re-examination provides a distinct viewpoint and enhances one's overall understanding of the IBS concept [13, 20, 21].

Consequently, negative perceptions, including high expenses, delays, supply shortages, subpar architecture, and outdated prefabricated housing, have adversely affected public opinion on IBS [2, 9, 14]. An innovative IBS block house has been developed, aiming to address the shortcomings of traditional IBS methods while showcasing its advantages to both construction stakeholders and the public [2, 11, 15]. This block house utilizing an IBS employs a precast reinforced concrete block system that is tailor-made to ensure the safety of occupants in the face of natural disasters and unforeseen risks. It incorporates design elements that enable quick assembly and disassembly of the structure [2], reducing waiting periods and errors while enhancing construction quality. Figure 2 illustrates the patented IBS block house, registered under intellectual property rights [2].

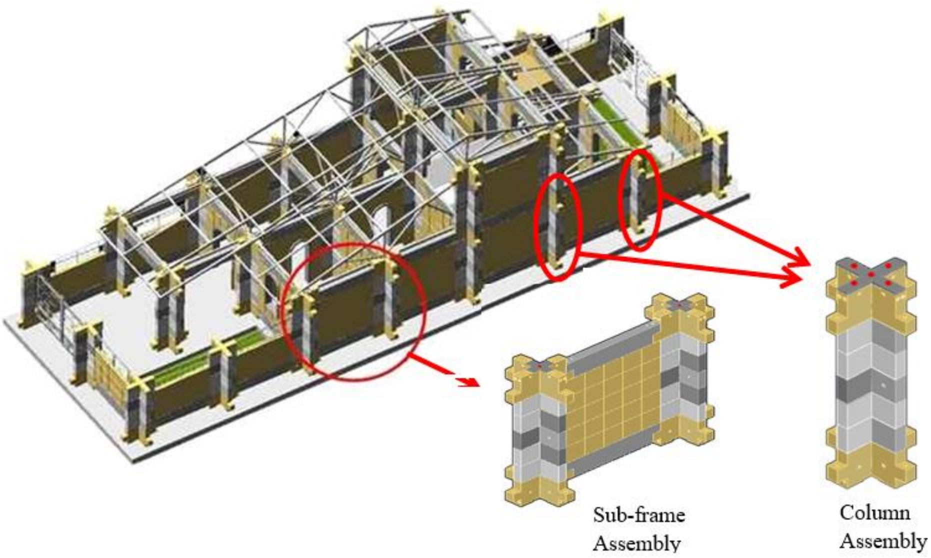


Figure 2. IBS Block House [2]

Advantages of precast concrete structures are control of quality, efficient use of materials, better management of construction, and cost-saving [1, 9]. Due to the demand for increased construction space on sites, labor constraints, prolonged waiting times for concrete curing and hardening, and shortcomings in quality control, traditional cast-in-situ construction is gradually being replaced by the widespread adoption of precast concrete systems. However, precast concrete structures pose specific challenges, particularly in terms of lateral bracing [19, 22–25]. While they exhibit numerous similarities to cast-in-place concrete structures, they lack the inherent member-to-member continuity that imparts significant lateral stability [26]. Precast structures should be handled similarly to post and beam structures made of wood or steel [27–29]. This issue is exacerbated by the augmented dead weight of the structure, leading to an additional lateral force [17, 26]. Individual precast concrete elements are typically connected using steel devices embedded within the elements [5]. The construction of the structure becomes a matter of connecting steel to steel. In cases where load transfer for gravity resistance is confined to basic bearing, there may be no tangible stress function, primarily serving to keep the members in place during construction [1, 21, 30]. During lateral loading, it is anticipated that all connections will need to efficiently transmit shear, tension, bending, and torsion. Consequently, the seismic resistance of numerous connections commonly employed for gravity resistance alone is expected to be insufficient [31, 32].

Due to their weight, precast concrete spanning members might encounter specific challenges related to vertical accelerations. When inadequately restrained against upward movement, these members may dislodge from their supports [10, 23, 32]. Like wooden or steel frames, stability for precast concrete frames requires trussing, moment connections, or infill walls. If walls are employed, they should be restricted to masonry or concrete. The connections between the frame and any bracing walls need to be meticulously designed to ensure proper load transfers [9, 32, 33]. Despite the considerable advantages of Industrialized Building System (IBS) over conventional cast-in-situ construction, the fact that numerous IBS columns failed during earthquakes highlights the necessity for IBS columns to possess adequate ductility to withstand intense vertical and horizontal ground motions [2, 4, 34]. Thus, the column is one of the most critical concerns that should always be taken into consideration during the analysis and design stages [32, 34, 35]. Columns need to be engineered with sufficient strength and stiffness to endure horizontal forces. Conversely, the introduction of a truss-reinforced system in concrete members was innovatively spearheaded by Julius Kahn and officially patented on August 8, 1903 [7, 11]. Kahn's reinforcement system comprised rolled bars featuring "wings" that were cut and bent upward at regular intervals [7]. Put differently, Kahn hypothesized that his system operated in a bending manner similar to a Pratt truss. In this arrangement, the diagonal wings and primary longitudinal bars functioned as tension members, while the concrete served as vertical compression members. Furthermore, the diagonal wings served the dual role of acting as shear reinforcement at the ends of the members [1, 8, 15].

The precast concrete column elements, which consist of unreinforced precast concrete blocks, can be denoted as either precast columns or core columns. The latter classification involves a cast-in-place reinforced concrete core, as illustrated in Figure 3 [7]. Crafted by skilled workers in factories, the concrete blocks used to construct these columns undergo stringent quality control. The use of small blocks eliminates the need for on-site formwork or reinforcement cages. This design facilitates the straightforward, rapid, and precise assembly of blocks by unskilled individuals, particularly in rural areas. The approach not only ensures cost savings but also eliminates the necessity of hiring experienced construction workers.

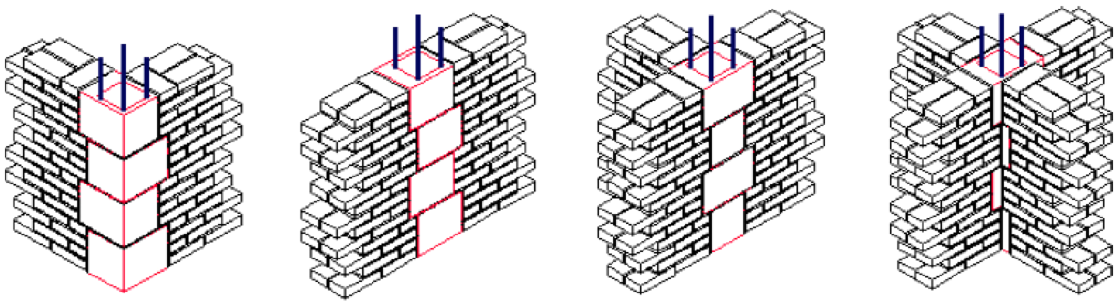


Figure 3. Fabricated pre-cast columns for various wall intersection scenarios [7]

Typically, there is an anticipation that both core columns and precast columns will offer cost savings in comparison to cast-in-place (CIP) reinforced concrete columns. Moreover, it is expected that the structural performance of these prefabricated columns will closely resemble that of CIP-reinforced concrete columns [7]. The steel truss embedded in fiber-reinforced concrete (FRP) demonstrates commendable performance under load reversals due to the support provided by the FRC to the truss chords and web members, preventing buckling [31]. Moreover, Fiber-Reinforced Concrete (FRC) enhances shear resistance and provides fire protection to the enclosed steel elements. Experimental assessments involving FRC-encased steel truss beams and frames subjected to reversed cyclic loading demonstrated their exceptional seismic response, establishing their suitability for seismic-resistant construction [7, 12, 34]. The special-shaped column consists of a cross-shaped, L-shaped, or T-shaped column, as shown in Figure 4, which illustrates the IBS sub-frame model comprising two columns and two beams. The dimensions of the scaled beam are 500 mm x 100 mm with a thickness of 40 mm. The beam can be assembled and disassembled by loosening the bolts and nuts that connect it to the column, enabling easy reuse whenever necessary [2, 26]. These types of columns are usually related to the bearing capacity and seismic performance [26].

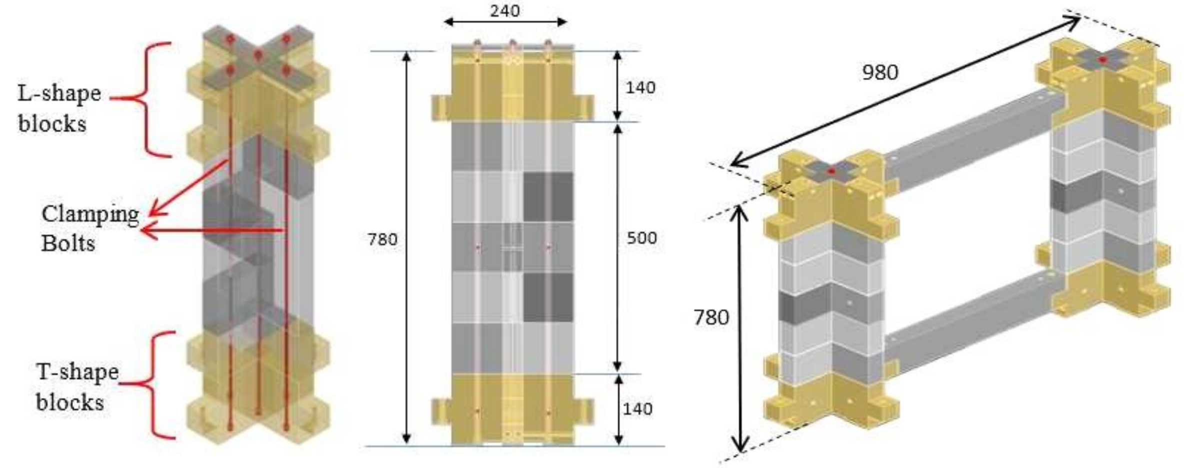


Figure 4. Block Work Formation of IBS Models – All dimension in mm [2]

The specially shaped column is extensively employed in numerous countries for the shear walls of high-rise buildings, owing to its advantages such as high strength, stiffness, excellent ductility, and structural convenience [3, 12, 36]. Moreover, it is also said that a special-shaped column is suitable for saving architectural space and aesthetic purposes [34, 37-39]. The main objective of this research is to investigate the performance of IBS cruciform columns with dual-reinforced systems subjected to lateral loads [4, 21, 34]. The dual-system reinforcement incorporates the main reinforcement with a truss system embedded in the column to enhance its resistance to lateral forces caused by wind and earthquakes [31]. Three-dimensional finite element simulation was used to investigate the displacement of the prototype model of a 1:5 scaled IBS cruciform column [23, 24, 31–33]. IBS cruciform column specimens were modeled and analyzed linearly using LISA software [36].

To tackle this concern, this paper introduces the IBS cruciform column (depicted in Figure 5) to enhance lateral load resistance. The IBS cruciform column consists of four prefabricated components with interlocking joints, assembled using post-tension bolts, to form a column with a crucifix plan. Two types of joints, external and internal interlocking joints, are employed in the column. External joints are utilized for column-beam connection, while internal joints are employed to assemble the IBS components, creating clamping force to securely bind the components together.

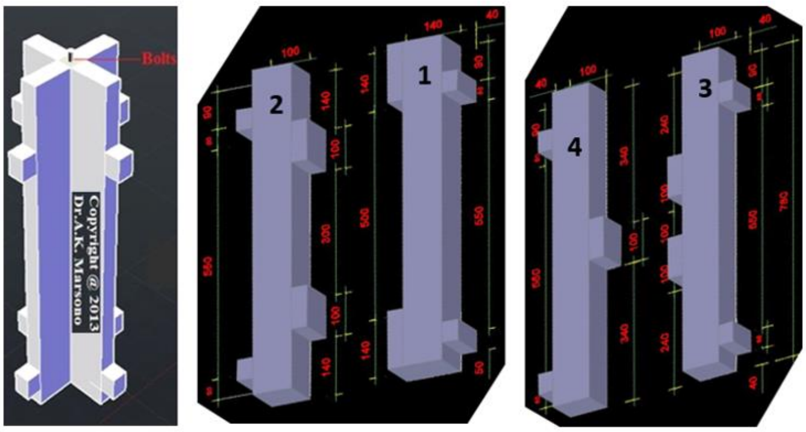


Figure 5. (a) Assembly IBS Block Work Column, and (b) detailing of components 1 & 2, and (c) detailing of components 3 & 4 – All dimension in (mm)

Over an extended duration, the construction sector has consistently played a significant role in producing construction waste, presenting a persistent challenge in efficiently managing this waste to mitigate environmental pollution. Through prior research, efforts have been made to address this issue [15, 27, 33].

This research study extensively investigates the origination of construction waste in the context of erecting high-rise structures, employing three distinct construction methodologies: the Conventional Construction Building System, the Mixed System, and the Industrialized Building System (IBS).

Most notably, the Industrialized Building System (IBS) emerges as the construction approach with the most minimal waste production, amounting to a mere 0.016 tons of construction waste per square meter of floor space [3]. On the flip side, the Mixed System and Conventional Construction yield 0.030 and 0.048 tons/m², respectively. Furthermore, the Industrialized Building System (IBS) stands out with a remarkable construction waste usage efficiency, reaching 94.1%, and only 5.9% of the total construction waste finds its way to landfills. Thus, emphasizing the significance of employing the IBS system as a sustainable component that minimizes construction process-generated waste.

Also, this transition towards IBS holds substantial promise for enhancing the environmental performance of the construction industry, aligning with the objectives of sustainable development. Ultimately, this research aims to fortify the commitment of the construction industry towards environmental sustainability.

2. In Comparison to Prior Studies

When juxtaposed with earlier investigations on the Lateral Displacement Behavior of IBS (Industrialized Building System) Precast Concrete Elements Reinforced with Dual Systems, certain notable distinctions emerge. Prior studies may have focused on different structural configurations, material compositions, or testing methodologies. Variations in experimental setups, boundary conditions, and analytical approaches across these studies contribute to a spectrum of findings and interpretations. Also, the collective insights gained from previous studies underscore the multifaceted nature of the Lateral Displacement Behavior in IBS Precast Concrete Elements reinforced with Dual Systems. While each investigation provides valuable contributions to the understanding of this structural aspect, it is essential to acknowledge the diversity in methodologies and contexts. A comprehensive synthesis of these findings can guide future research endeavors, facilitating a more nuanced comprehension of the factors influencing lateral displacement behavior and enhancing the overall robustness of structural design and analysis in the realm of IBS precast concrete elements. Table 2 provides a comprehensive synthesis comparing the research publication year, Country, Columns/Model Fabrication, Tested specimen, and IBS classification presentations from previous research studies with the current research.

Table 2. A comprehensive synthesis comparing the research from previous research studies with the current research

Authors	Country	Columns/Model Fabrication	Tested specimen	IBS classification
Current study	Egypt	IBS block work column	Pre-cast concrete columns	Pre-cast concrete framing
Wang et al. (2017) [7]	China and New Zealand	Core columns and Precast columns	Wall with fabricated concrete column	Prefabricated timber framing system - Block work system
Kamar et al. (2011) [4]	Malaysia	Nil	Nil	Prefabricated timber framing system - Pre-cast concrete framing - Block work system
Baghdadi et al. (2020) [28]	Malaysia	Nil	Nil	Prefabricated timber framing system - Block work system -
Beatriz da Silva et al. (2020) [40]	Malaysia	Column Model and Sub-frame Model	Pre-cast concrete framing	Pre-cast concrete framing
Khademi et al. (2023) [41]	Iran	Multistorey RC shear wall	Pre-cast shear wall	Nil
Hasan et al. (2023) [16]	Malaysia	Pre-cast wall with dual boundary elements	Pre-cast wall	Pre-cast concrete wall system
Al-Aidrous et al. (2023) [20]	Malaysia and Indonesia			

3. Research Significance

The current research on the lateral Displacement Behavior of IBS Precast Concrete Elements Reinforced with Dual System holds significant importance for various reasons:

a. ***Structural Integrity:*** The study investigates the lateral displacement behavior of IBS (Industrialized Building System) precast concrete elements. This research is crucial to enhancing our understanding of how these building components respond to lateral forces, such as those generated by wind or seismic activity. By doing so, it contributes to ensuring the structural integrity and safety of buildings constructed using IBS techniques.

b. ***Building Resilience***: Given the increasing frequency and intensity of natural disasters, understanding how precast concrete elements behave under lateral forces is vital for designing resilient structures. This research can inform building codes and construction practices to make structures more resistant to lateral displacements and, thus, better able to withstand these external forces.

c. ***Cost and Time Efficiency***: Precast concrete elements are often used in construction for their efficiency in terms of cost and time. Studying their lateral displacement behavior provides insights into optimizing their design and deployment, potentially reducing material waste and construction time while maintaining safety standards.

d. ***Sustainability***: Sustainability in construction is a global concern. Research in this area can lead to the development of more sustainable building practices. Understanding how IBS precast concrete elements behave laterally can lead to innovative designs that reduce resource consumption and waste generation.

e. ***Safety Regulations***: The results of this research can contribute to the establishment or revision of safety regulations for IBS construction. This can be particularly important for regions prone to seismic activity, where minimizing lateral displacement is critical for preventing structural damage and protecting lives.

f. ***Architectural Freedom***: Insights into the lateral displacement behavior of precast concrete elements can also provide architects and designers with valuable information. It allows them to make informed decisions about the design of structures, ensuring that they not only meet safety requirements but also offer architectural freedom.

In summary, this research on the lateral displacement behavior of IBS precast concrete elements reinforced with a dual system is significant because it addresses critical aspects of safety, sustainability, efficiency, and architectural design in the construction industry, contributing to safer and more resilient buildings. Also, Figure 6 illustrates the research methodology flowchart.

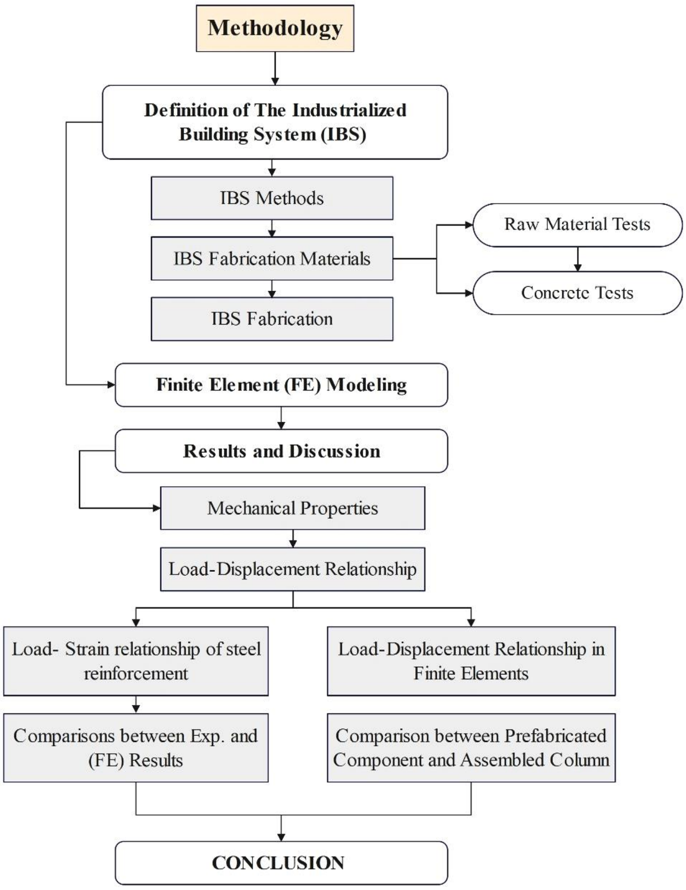


Figure 6. The flow chart of the research methodology

4. Material and Methods

The compression test for the concrete was conducted for cylinder specimens of 100 mm in diameter and 200 mm in height based on ASTM C39 [42] to determine the compressive strength and Young's modulus of the concrete, as shown in Figure 7. Cylinders were cast using fresh concrete of C30 grade. The outcomes of compressive strength and modulus of elasticity were then employed in the finite element modeling conducted in this study. The materials used are detailed below, outlining their properties and specifications:

Figure 7. (a) Compression test and (b) Young's modulus test

The first set of concrete mixes employed natural aggregate (NA), comprising coarse aggregate derived from naturally crushed dolomite with a nominal maximum size of 19 mm. The fine aggregate in this set was natural sand, characterized by a specific gravity of 2.58 and a size distribution ranging from 0.15 to 1.2 mm. The natural sand utilized adheres to the standard specification ASTM C33/C33M-08 [43]. The grading size distribution of used natural coarse aggregate (NA) and fine aggregate (FA) is illustrated in Figure 8, while the physical and mechanical properties are presented in Table 3.

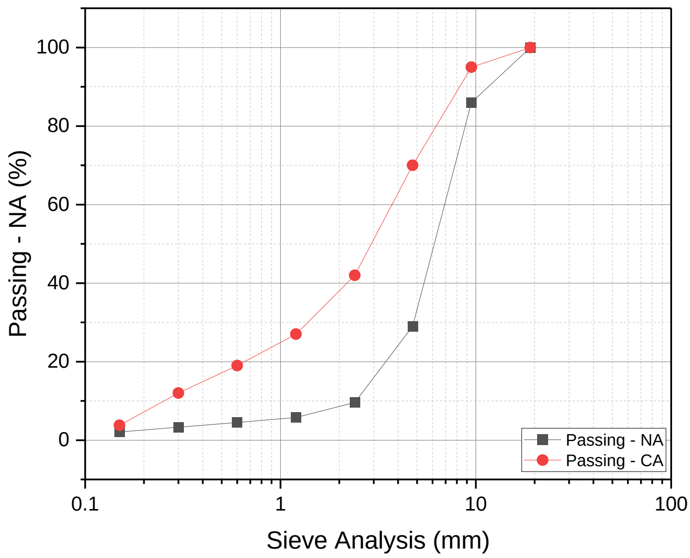


Figure 8. Particle size distribution for NA and CA

Table 3. Mechanical and Physical Characteristics of Natural Aggregate (NA) and Concrete Aggregates (CA)

Property	Natural Aggregate	
	Crushed dolomite	Sand
Specific gravity	2.65	2.58
Volume density	1430	1612
Water absorption%	0.86	1.9
Los Angeles abrasion %	17.56	-
Crushing value %	17.93	-

For the fabrication of IBS Block Work components, an 18-mm-thick plywood mold with dimensions of 810×896 mm was employed as the bottom of the mold. Solid wood pieces with a cross-section of 40×40 mm and plywood measuring 40×18 mm was combined to create the shapes of the four prototype components at a scale of 1:5. Interlocking joints between the IBS blockwork components were achieved by interlocking pipes fixed into holes drilled in the solid wood. The interlocking joints were connected using a bolting system, as illustrated in Figure 9. The components were reinforced with steel of grade 250 N/mm^2, utilizing 6 mm-diameter rods as the main reinforcement. These rods were bent into a rectangular shape and placed longitudinally at the center of the concrete layer along each component and interlocking joint. Strain gauges were installed in components 1 and 2 for all four specimens. Given that components 1 and 2 are situated in the direction of the applied load, the strain gauges measured the strain in the main steel reinforcement in relation to the lateral load applied. Subsequently, concrete of grade C30 was poured into the mold. Curing was performed by spraying water on the surface and covering the concrete with a moist cloth. After 28 days, the components were assembled using a 5mm tension bolt with two nuts at the top and bottom of the column. The post-tension force value was calculated as $0.8f_{ck}$ of the concrete strength and will clamp together, forming a crucifix plan without crushing the concrete. The force value was converted to a torque value and applied using a torque machine.

The specimens will undergo horizontal testing to examine their deformation in the elastic state. A lateral push-up test was performed on a single component, "S2," and the assembled Block Work Column, respectively. The lateral load was applied through a 100-mm-wide channel of steel at the position of 0.147 of the column's top edge, which was cast as a corbel to support the beam. A hydraulic jack was employed to apply the load, where the hydraulic jack was connected with a load cell, as depicted in Figure 10. LVDT and laser distance measuring devices were utilized to measure the displacement, as illustrated in Figure 10. The strain gauges, load cell, and LVDT were linked to the portable data logger.

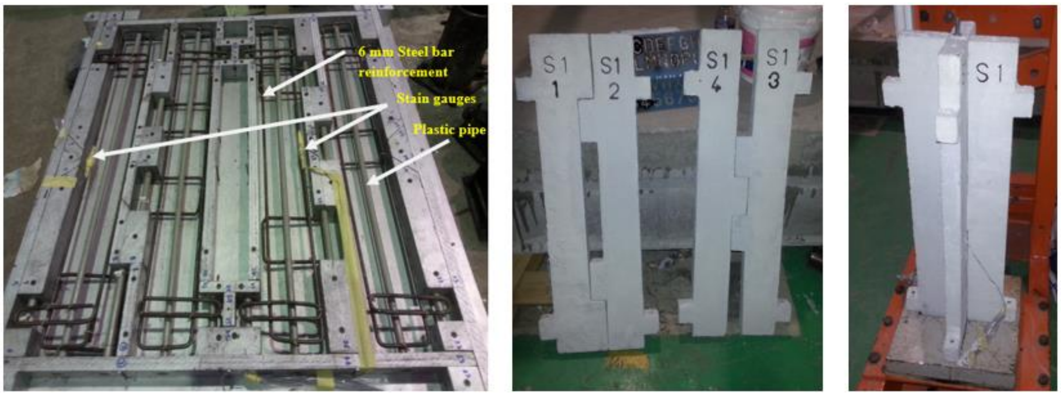


Figure 9. (a) Reinforcement, strain gauges and pipes arrangement in the mold, (b) Interlocking component 1 & 2, and 3 & 4, and (c) Assembled IBS Block Work

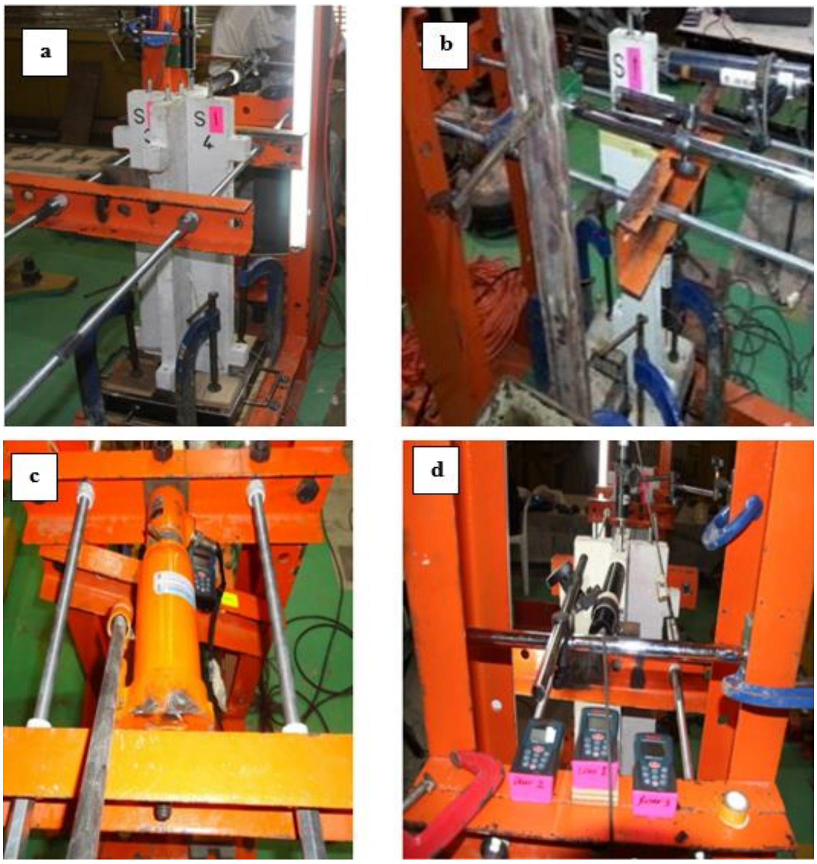


Figure 10. Set up of the push up of (a) IBS block work column (b) single component "S2", (c) Hydraulic jack and load cell, and (d) LVDT and lasers distances

Static general finite element analysis, utilizing LISA software, was employed to validate the lateral displacement results of the IBS Block Work Column (SC1) and its component (S1). Subsequently, the influence of the dual system of reinforcement on the lateral displacement behavior was investigated, incorporating three different truss shapes of the reinforcement, as illustrated in Figure 11. In the modeling process, solid element type (hex8) was utilized to construct the mesh of concrete elements, while the (line2) frame/truss element was employed to establish the mesh of steel reinforcements, pipes, and bolt connections. Figure 12 depicts the locations of elements, loads, and constraints for IBS Block Work columns. Figure 13 illustrates the four distinct dual reinforcement systems of one prefabricated component, denoted as SC1 (control model 1), SC2, SC3, and SC4. Figure 13 illustrates the four distinct dual reinforcement systems for the assembly IBS work column identified as S1 (control model 2), S2, S3, and S4. The boundary condition at the base of the modeled specimen is assumed to be rigidly constrained, applying a zero value of displacement in the global -X, -Y, and -Z directions for all nodes located in the base components. No boundary conditions are set between the components of the column, as the four components are held together using steel bolt elements modeled to pass through the pipe element from top to bottom of interlock joints. All pipe elements, steel-reinforced elements, and steel connection bolt elements share nodes with concrete elements. The loadings were applied horizontally at 90 mm of the column height (0.147 top heights of the column), as depicted in Figure 11. The load was applied to the specimens with a 2.0 kN increment until reaching 28.0 kN to accurately establish the relationship between load and deformation.

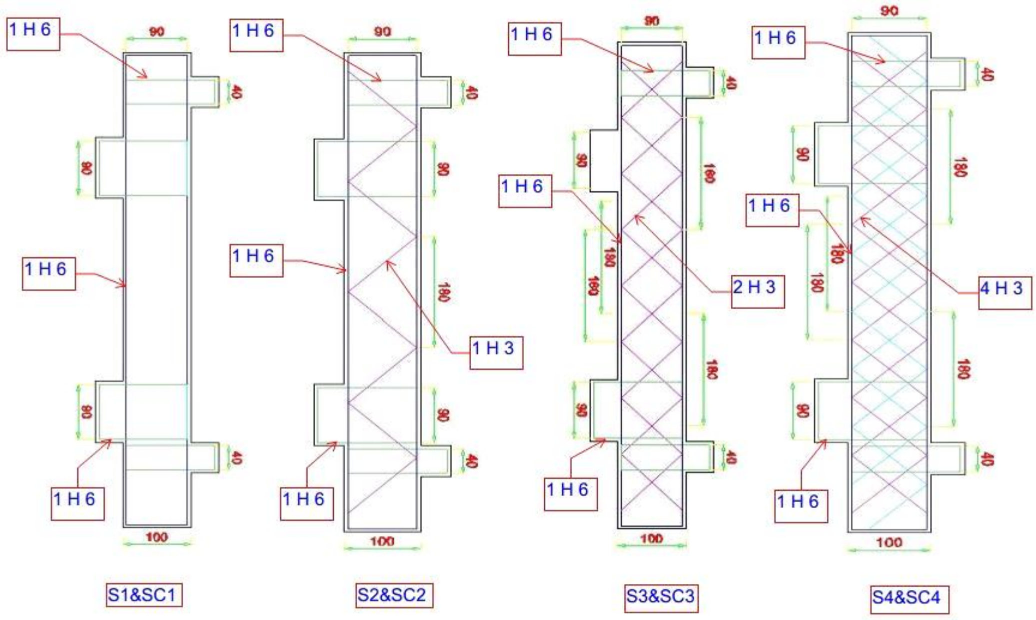


Figure 11. Details of dual system Reinforced of specimens

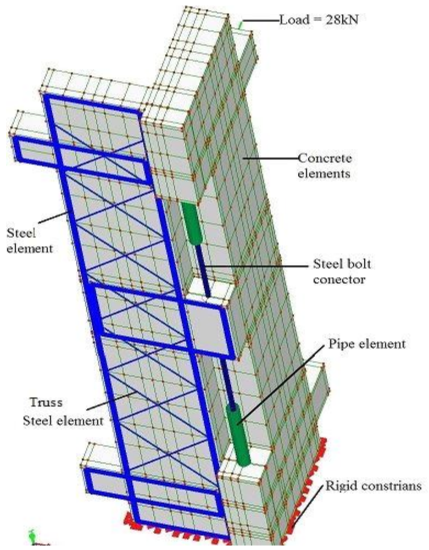


Figure 12. Load and constraint locations of IBS Block Work column

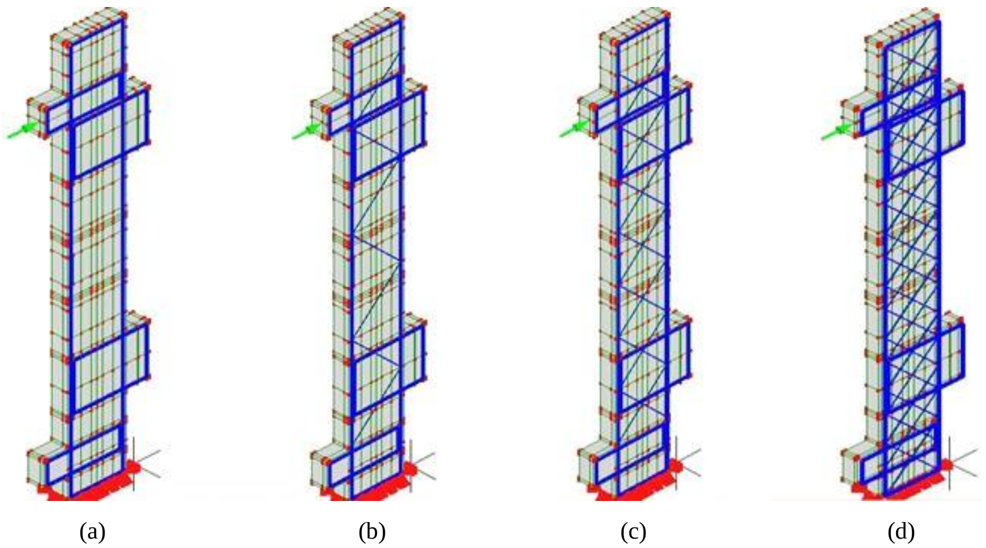
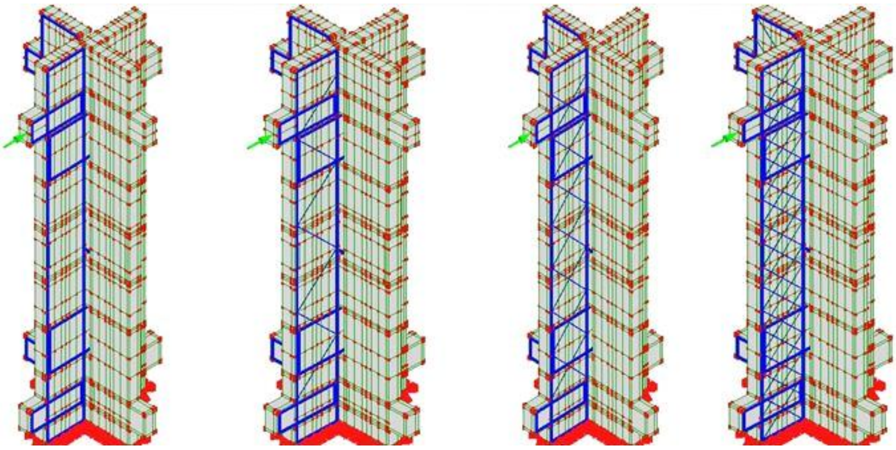


Figure 13. Modeling of one prefabricated component for different dual reinforcement specimens (a) SC1 – Control 1 (b) SC2, (c) SC3, and (d) SC4



(a) (b) (c) (d)

Figure 14. Modeling of different dual reinforcement systems for the assembly IBS work column (a) S1 – Control 2 (b) S2, (c) S3, and (d) S4

5. Results and Discussion

5.1. Mechanical Properties

The specimen's average compressive strength was measured at 26.42 N/mm², while the equivalent compressive strength of the cube stood at 31.70 N/mm². The maximum applied load reached 285 kN. In the ultimate state, the maximum strain was determined to be 1900 μm, and the maximum stress was recorded at 36 N/mm². The Young's modulus, derived from the elastic zone in the stress-strain curve, was calculated to be 24258 N/mm². These results, encompassing the compressive strength and Young's modulus of concrete elements, steel reinforcement elements, steel bolt connector elements, and plastic pipe elements (see Table 4), were employed in LISA as isotropic mechanical properties for the finite element modeling in this study.

Table 4. The mechanical properties of elements

Element	Concrete	Main reinforced	Truss strips reinforced	Plastic Pipe	Bolt Connector
Young's modulus, E (N/mm^2)	24258	226550	113720	400000	226550
Poisson's ratio, v	0.2	0.3	0.3	0.33	0.3
Density, ρ (kg/mm^3)	2.4×10^{-5}	7.9×10^{-5}	7.7×10^{-5}	1.2×10^{-5}	7.7×10^{-5}
Thermal expansion coefficient, t °C	9.9×10^{-6}	1.2×10^{-5}	1.2×10^{-5}	3×10^{-5}	1.2×10^{-5}

5.2. Load-Displacement Relationship

Figure 15 depicts the front view of the IBS block work column specimen (LS1) post-testing. The load-displacement relationship and uplifting of the specimens from the base are illustrated in Figures 16 and 17. Displacement measurements were taken at the top horizontal point of the column height and two vertical points to assess specimen uplifting: the first point on the top side of the specimen and the second point at the top of the steel base plate. Data analysis revealed that at a 28 kN lateral load, the maximum displacement was 16.5 mm for the single-component specimen (LC1) and 4.5 mm for the IBS block work column specimen (LS1). Simultaneously, the maximum uplifting displacement at the top side of specimen LC1 was 1.2 mm, and it was 1.4 mm on the top side of specimen LS1. The maximum uplifting displacement at the top of the steel base plate for specimen LC1 was 0.3 mm, while it was 1.2 mm for specimen LS1. These findings align with the cited sources [1, 20, 34].

Figure 15. Failure of IBS block work column specimen (LS1) due to 28 kN lateral load

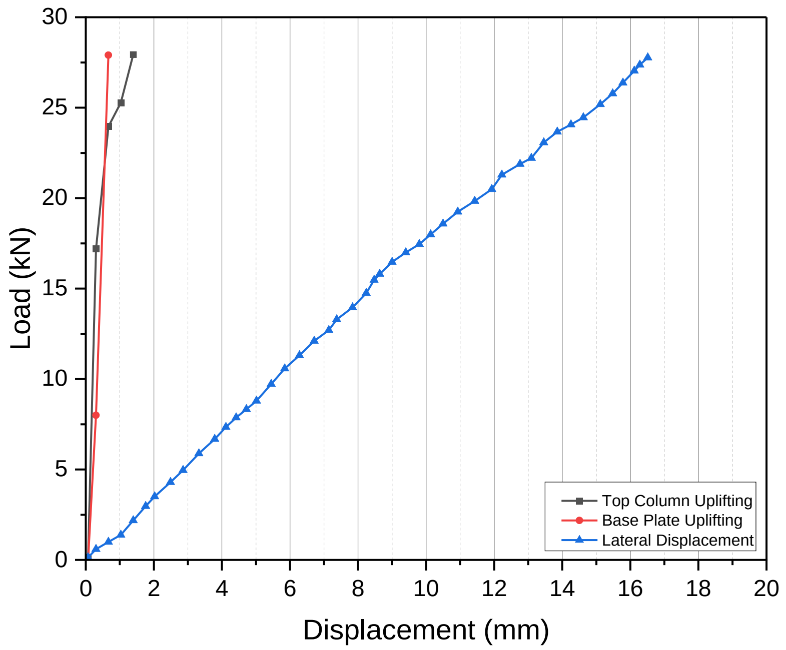


Figure 16. Load-displacement relationship of specimen LC1

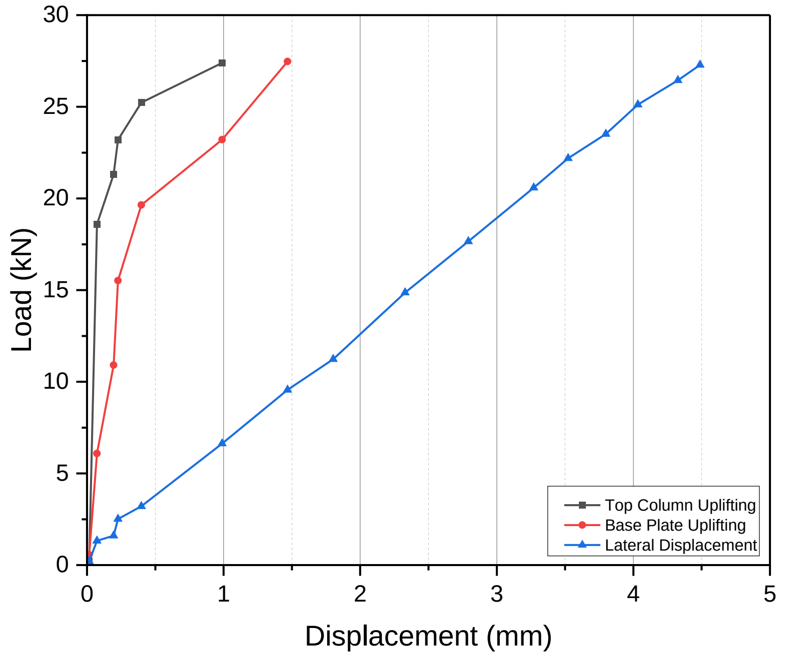


Figure 17. Load-displacement relationship of specimen LS1

5.3. Load- Strain Relationship of Steel Reinforcement

Figure 18 illustrates the maximum strain in the main steel reinforcement aligned with the direction of the applied lateral load. The single-component specimen (LC1) reached a maximum strain of 38 µm at the applied load of 28 kN. For the IBS block work column specimen (LS1), the maximum strain in the component subjected to the lateral load attachment reached 83 µm. Simultaneously, the component in the same specimen but located opposite to the applied lateral load direction reached a maximum strain of 38 µm. As the yielding strain point of steel is at 0.002 mm, the strain in the reinforcement of the specimens remains in the elastic state without permanent deformation.

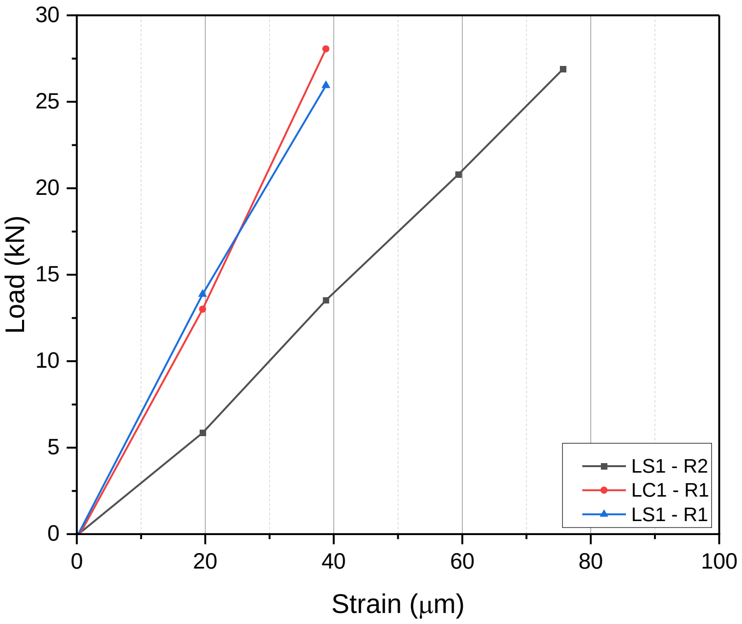


Figure 18. Load- strain relationship of steel reinforcement

5.4. Comparisons between Experimental and Finite Element Results

Figure 19 (a) and (b) depict the behavior and displacement distribution of the single specimen (SC1) and IBS block work column (S1), respectively, under a 28 kN lateral load. For verification purposes, the experimental displacement results of the single-component specimen (LC1) were compared to those from the modeling of the single-component specimen (SC1), as shown in Figure 15. Similarly, the experimental displacement results of the IBS block work column specimen (LS1) were compared to those from the modeling of the IBS block work column (S1), as shown in Figure 21. The convergence between the displacement results from the experimental and modeling results is acceptable, with a percentage of similarity of 91.7% and 88.5%, respectively. Therefore, with the model verified, modeling of the dual-system reinforced cruciform IBS column can be used as an alternative method instead of casting several specimens, saving casting time and cost.

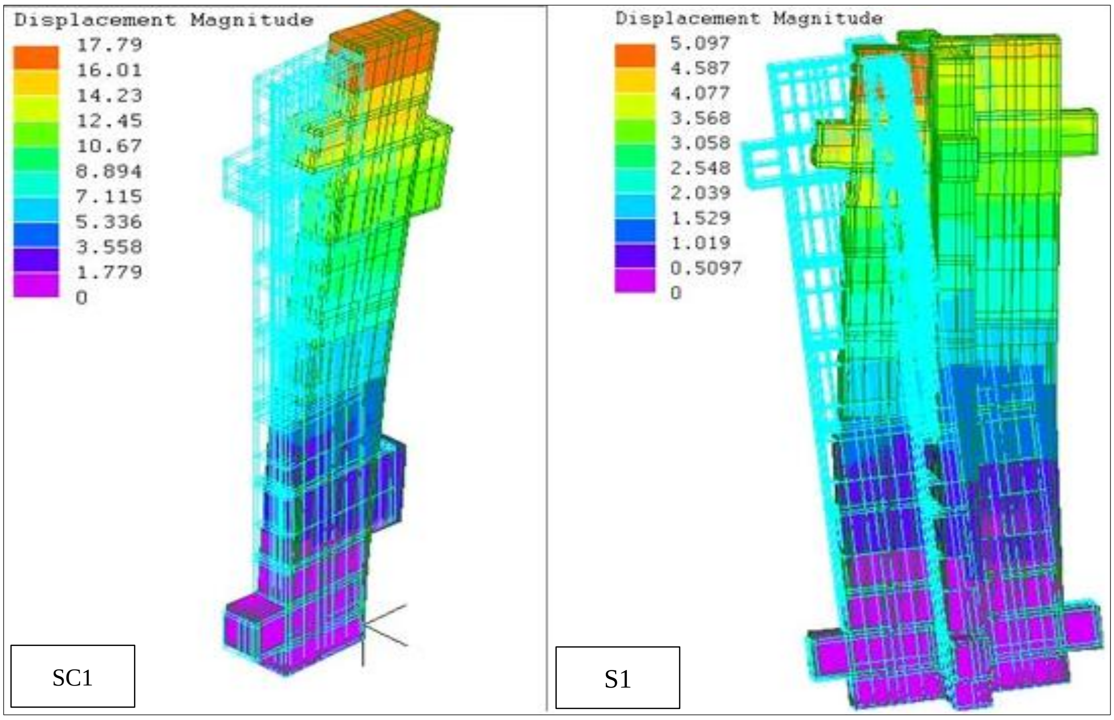


Figure 19. Displacement distribution due to 28 kN lateral load of specimen SC1 (a) & S1 (b), respectively

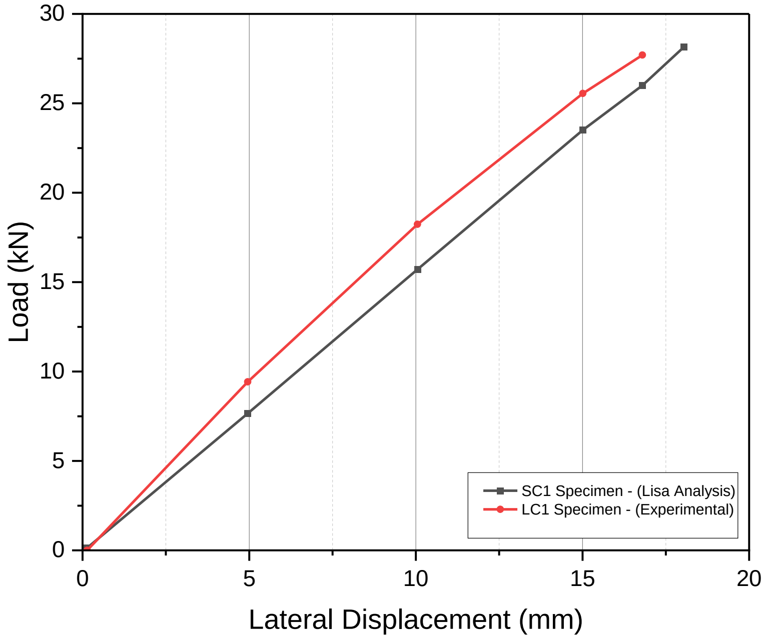


Figure 20. Shows the displacement distribution of specimen SC1 & LC1 due to 28 kN lateral load

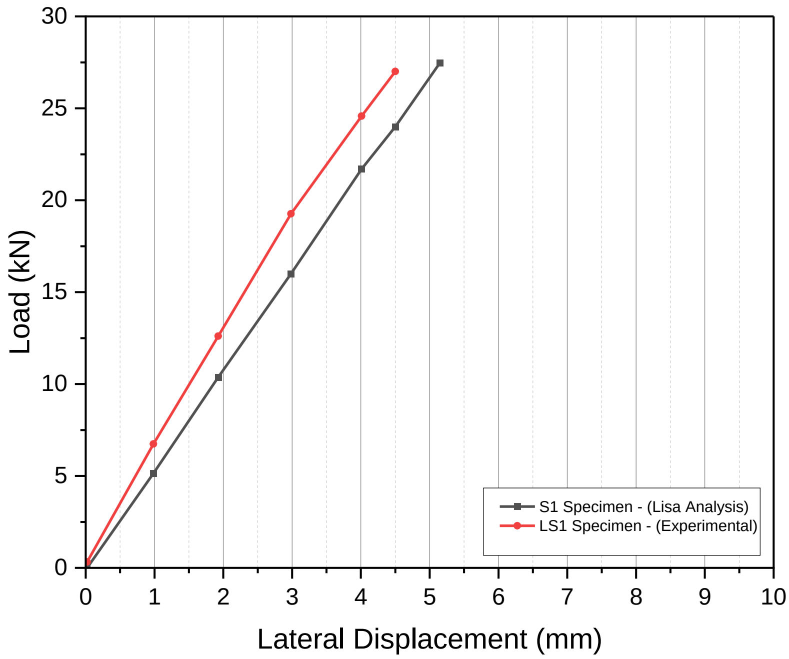
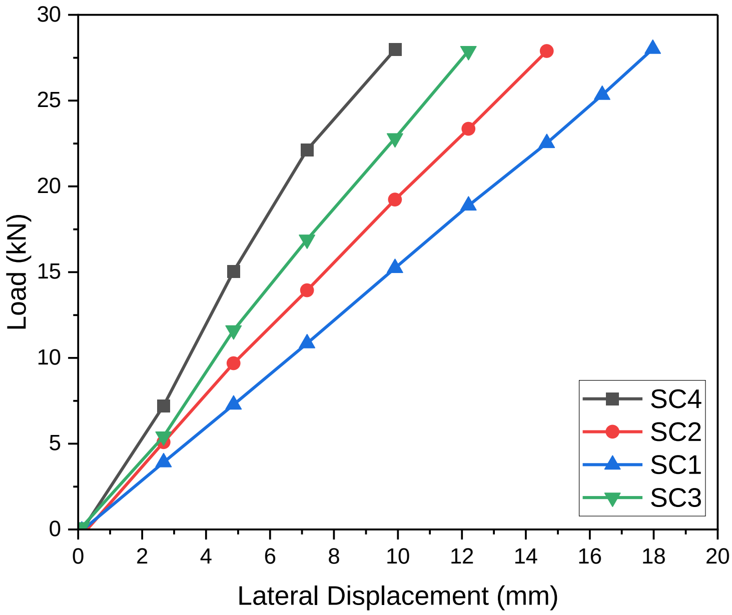


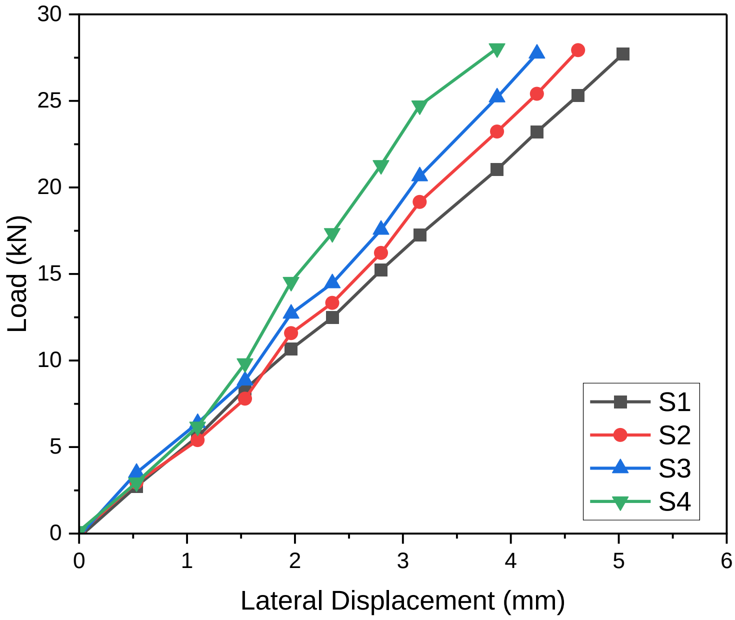
Figure 21. Shows the displacement distribution of specimen LS1 & S1 due to 28 kN lateral load

5.5. Load-Displacement Relationship in Finite Elements

The load-displacement relationship of the specimens is depicted in Figure 22 (a) and (b). Figure 22 (a) indicates that specimens SC2, SC3, and SC4 exhibited less displacement compared to the control model (SC1). Similarly, Figure 21 (b) shows that specimens S2, S3, and S4 also had less displacement when compared with control model 2 (S1). The reduction factors of displacement for specimens SC2, SC3, and SC4 were found to be 0.197, 0.323, and 0.487, respectively, while the reduction factors of displacement for specimens S2, S3, and S4 were found to be 0.095, 0.171, and 0.289, respectively. This reduction illustrates that higher steel reinforcement density reduces lateral displacement, leading to higher resistance to lateral load.



(a)



(b)

Figure 22. Load-Displacement Relationship of assembly IBS Block Work Column

5.6. Comparison between Prefabricated Component and Assembled Column

The load-displacement relationship comparison between single-component specimens and the IBS Block Work Column is depicted in Figure 23. The figure illustrates that the assembled specimens of the IBS Block Work Column have significantly reduced displacement compared to that observed in the single-component specimens with the same amount and truss shape of reinforcement. The displacement reduction percentages are summarized in Table 5.

Table 5. Displacement reduction due to assemble four components to be one column.

SP. Relation	LC1 LS1	SC1 S1	SC2 S2	SC3 S3	SC4 S4
% Displacement Reduction	71.15	71.34	67.69	64.87	60.33

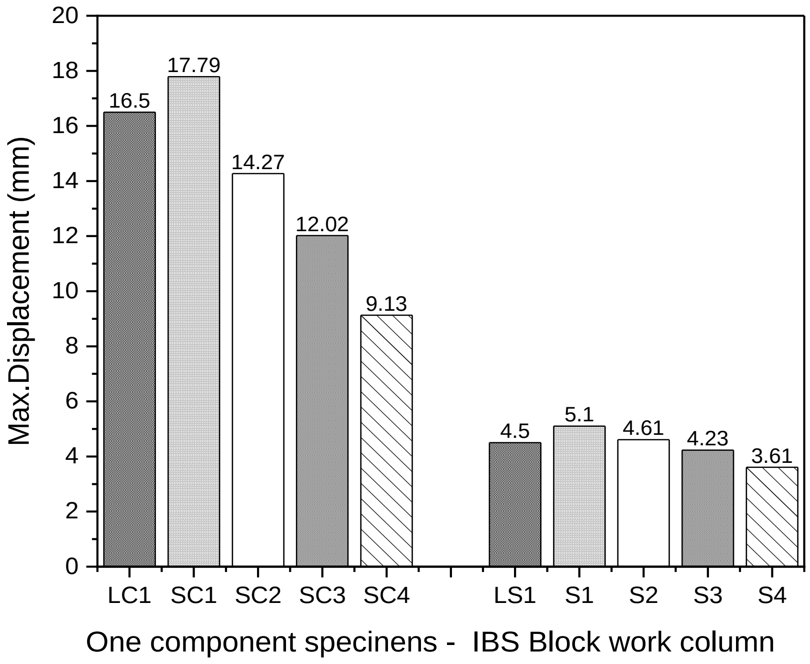


Figure 23. Displacement comparison between one component and assembly IBS Block Work Column

5.7. Contrary to the Results of Previous Investigations

Certain investigations have delved into the viability of employing IBS, which embodies a sustainable and innovative approach utilizing environmentally friendly materials for the repetitive manufacturing of reinforced concrete components.

Marsono et al. [21] found that IBS is a sustainable and innovative method that uses green materials to make reinforced concrete components in a repetitive way. The components are made in a factory with strict quality control. To ensure the reliability and quality of the IBS components, they have to be tested by full-scale experiments and FEA according to the Eurocode standards. Also, Marsono et al. [21] mentioned that the new IBS beam had an experimental ultimate capacity of 133 kN and a mid-span deflection of 24.13 mm. The frame deformation patterns were similar in both the experiment and the FEA. The yielding of the steel plate, CRC, and bolts and nuts of the U-shaped beam was also consistent in both methods. Based on these results, further development can rely on FEA alone to save on the costs of physical tests. This paper presents the standard test of IBS products made with seasonal steel molds.

Lee & Ma [2] successfully delineates the dynamic behavior and seismic performance of IBS block house subsystems. Also, their study delves into the natural frequencies of IBS columns and beams as well as examines the acceleration response, displacement response, and hysteresis response of both column and subframe models. The results from finite element simulations align closely with experimental findings, particularly in terms of displacement response and the identification of failure mechanisms [2, 20, 21].

Esmaeili et al. [11] and Lachimpadi et al. [3] stated that the precast reinforced concrete frame falls under the category of Industrialized Building System (IBS) but is constrained in its assembly, specifically in the precast beam-to-column connection (PBC). These constraints present various challenges and lead to the design of pinned connections that are inappropriate for moment-resisting frames (MRFs) in regions with high seismic activity. Also, Bester et al. [11] mentioned that the test results demonstrated that the proposed precast beam-to-column connection (PBC) displayed superior load-carrying capacity, energy dissipation, and ductility in comparison to its equivalent IBC.

It satisfied all the seismic criteria specified in ACI 374.1-05 for moment-resistant connections. Following that, finite element simulations were carried out using ATENA software to confirm the validity of the test results. In this stage, the finite element analysis predictions for load-carrying capacity, cracking patterns, and strain values showed significant consistency with the test results. The influence of factors such as concrete compressive strength, axial force in the column, and length of beam end plates was investigated. Elevated concrete strength and axial force were associated with an augmentation in load-carrying capacity and a decline in strength within the beam-column joints, respectively.

6. Conclusions

The Industrialized Building System (IBS) represents a sustainable and innovative approach that employs repetitive manufacturing with environmentally friendly materials for molding reinforced concrete components. Manufacturing these components in a factory allows for stringent quality control. To ensure the production of reliable IBS components that meet structural engineering standards and diverse practice requirements, various full-scale IBS experimental tests and Finite Element Analysis (FEA) are essential.

The IBS Block Work Column specimens in assembly demonstrated reduced deflection in comparison to their individual component counterparts. The percentage of displacement reduction reached up to 71.34%, and this figure tends to decrease with an increase in the amount of truss-shaped reinforcement:

- In the elastic state, the dual system reinforcement has effectively minimized deflection caused by lateral forces. The percentage of displacement reduction reached up to 48.7% for individual component specimens and 28.9% for the assembled IBS Block Work Column specimens.
- The assembled IBS Block Work Column specimens exhibited lower deflection compared to the individual component specimens. The displacement reduction percentage reached up to 71.34%, and this percentage tends to decrease as the amount of truss-shaped reinforcement increases.
- While the deformation of the column model reached 4.6 mm for the assembled IBS Block Work Column specimen and 16.5 mm for the individual component under a 28 kN lateral force, it's noteworthy that the longitudinal steel bars remained within the elastic range, and no cracking of the cover concrete was observed.
- The FEM analysis can predict the behavior of the IBS Block Work Column in an elastic state with good convergence.
- The high cost associated with designing economically viable molds and manufacturing small quantities of components for IBS makes it less feasible in comparison to readily available local raw materials at lower prices for conventional construction. Also, the ease of obtaining cost-effective local raw materials, such as sand, aggregates, timber, and suitable plywood, is a notable advantage of conventional construction when compared to the more expensive manufactured components of IBS.
- The existence of unauthorized landfills offers lower disposal rates for construction waste compared to the elevated costs at licensed landfills, which are limited in number. Additionally, the accessibility of affordable foreign labor.
- There is a scarcity of demand for recycled construction materials in the Malaysian construction industry due to the absence of construction standards for recycled materials.
- Additional research is necessary to demonstrate the advantages to contractors, ultimately promoting the adoption of IBS as the preferred choice within different countries construction industries.

7. Declarations

7.1. Author Contributions

Conceptualization, M.Y.M.A., A.K.M., and A.A.A.A.; methodology, W.F.E., M.Y.M.A., and A.K.M.; formal analysis, M.Y.M.A. and A.A.A.A.; data curation, W.F.E., S.E., and A.K.M.; writing—original draft preparation, A.K.M. and S.E.; writing—review and editing, S.E. and A.A.A.A.; supervision, M.Y.M.A. and A.K.M. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding & Acknowledgements

The authors confirm that the data applied in this study is primary data and were generated at the building materials laboratory of Kingdom University in Bahrain in cooperation with University Teknologi Malaysia, Johor, Malaysia. The authors would like to acknowledge that this research work was partially financed by Kingdom University, Bahrain from the research grant number 2023-10-008.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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