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Structural behaviour of hollow core reinforced concrete (HCRC) short column under static load

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ABSTRACT

The high strength-to-weight and low self-weight ratio of Hollow Core Reinforced Concrete (HCRC) short columns have made them a popular choice for application in construction. Nevertheless, little is known about how HCRC short columns behave when subjected to static loads. This is because HCRC short columns are a relatively recent type of structural member, and there has been little research into how well they behave when subjected to static loads. Given that HCRC short columns are made of composite material, it poses one of the difficulties in understanding their behaviour when subjected to static load. The complex relationship between the steel reinforcement and concrete core potentially affects the column's ability to support loads and failure more. The purpose of this research is to evaluate their failure mechanisms and assess the structural performance under static load. Finite element models with different configuration are modelled which can simulate the complex behaviour of reinforced concrete structures under static load. This study found that Square Hollow Core (SHC) and Circular Hollow Core (CHC) are known as the most affected columns in terms of displacement compared to Rectangular Hollow Core (RHC). Stress was critically found at the top section of the column and it reduced towards lower section. The finding is able to optimize load-bearing efficiency, reduce material usage, enhance stability, improve resistance, and be proposed as modern structural applications.

1. INTRODUCTION

Reinforced concrete (RC) is also designed according to established codes, ensuring safety and performance. By utilizing local materials and the potential for sustainability, reinforced concrete remains a preferred choice for diverse structural applications in modern architecture and engineering. Due to its elevated

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compressive strength, the structure is able to sustain substantial axial loads without concern for crack propagation or structural failure. The high-strength concrete provides the necessary compressive strength, while the embedded steel reinforcement helps to resist the tensile and shear forces acting on the structure [1]. In recent years, the use of high-strength concrete and advanced reinforcement techniques have further enhanced the load-bearing capacity and durability of reinforced concrete columns, making them an indispensable component as structural component to exhibit higher load capacity and high deformability [2]. Furthermore, it is necessary to propose new solutions that simultaneously compliment the cost and environmental impact in choosing the most sustainable design [3]. Furthermore, columns come into two types which are short and slender depending on its slenderness ratio. Short column is one where the materials' strength and cross-sectional dimensions determine the ultimate load at given eccentricity. The behaviour of slender columns is influenced not only by the strength of the materials used, but also by the dimensions of the cross-section and the column's slenderness ratio. The slenderness of the column can introduce additional bending moments due to lateral deformations, which must be accounted for in the design [4]. Reinforced concrete short columns are essential for structural stability, effectively resisting axial loads through the synergistic action of concrete and steel reinforcement. Their performance is influenced by slenderness ratios and failure mechanisms, necessitating careful design to ensure safety and durability [5]. As time passes by, evolution starts to spark and emerges a new type of column which is HCRC column. The behaviour of hollow HCRC structural elements under various loading conditions has been a topic of significant interest in the field of structural engineering. HCRC columns have garnered attention due to their unique design and potential applications in construction.

With this new type of column, many constructions become easier, and the overall cost can be reduced significantly. The usage of the hollow core reinforced column has been high since then because of its resistance attribute and visual appeal [6]. As proof, hollow core reinforced concrete column is being used considerably high for bridge piers, ground piles and utility poles. The reason for the circumstance is HCRC requires a minimal number of materials and provides higher structural efficiency compared to solid concrete columns and may cause local damages on such structures can propagate causing larger damages [7]. Therefore, this research is developed to analyse the failure mechanism and assess the structural performance of a HCRC short column under static load using finite element analysis. A study by [8] employed nonlinear FE analysis to investigate the load-carrying capacity and failure modes of HCRC short columns subjected to axial compression. The researchers developed a detailed FE model that considers the effects of concrete cracking, steel reinforcement, and the presence of the hollow core. Their results showed that the FE approach accurately captures the observed failure modes and provides reliable predictions of the ultimate load-bearing capacity of the columns.

Similarly, a comprehensive FE analysis of HCRC short columns under combined axial and lateral loading was conducted. The model incorporated the influence of various design parameters, such as concrete strength, reinforcement ratio, and core diameter, on the overall column behaviour. The study provided valuable insights into the interaction between axial and lateral loads, which is crucial for the design of HCRC columns in seismic-prone regions [9]. The use of FE analysis is to assess the fire resistance of HCRC short columns. The model accounted for the thermal and mechanical properties of the materials under elevated temperatures, enabling the researchers to predict the time-to-failure and failure modes of the columns under fire conditions. The findings from this study contribute to the development of design guidelines for HCRC columns in fire-resistant construction [10]. In addition to the above-mentioned studies, several other researchers have utilized FE analysis to investigate various aspects of HCRC short column behaviour, such as the effects of eccentricity [9], the influence of high-strength concrete [11], and the performance of HCRC columns in term of compressive strength and ductility [12].

In overall, the literature highlights a critical gap in understanding the nuanced behaviour of hollow core reinforced concrete (HCRC) short columns under static load, particularly in relation to complex loading conditions and failure mechanisms. Existing finite element (FE) models, while informative, often lack comprehensive analysis of structural behaviour which is able to lead the design inefficiencies and safety

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concerns. To address these challenges, this study aims to examine the usage of FE analysis techniques by focusing on key parameters such as displacement, stress-strain relationships, and energy dissipation behaviour. By enhancing the accuracy of these models, this research will provide engineers with more reliable tools for designing HCRC short columns, ultimately leading to improved structural safety and performance under static loads. In summary, this study not only addresses existing limitations in the literature but also proposes a better design practice in HCRC applications.

2. METHOD

In this research, Finite Element Analysis (FEA) is used as a research method. To successfully achieve the research's objectives, several steps have been taken which are summarized in Fig. 1. The design is based on a double-storey house. The column has a dimension size of 225 mm x 300 mm x 3000 mm in length, width, and height respectively. Therefore, in sequence to evaluate the failure mechanism and assess the structural performance of HCRC short column, three different shapes of hollow are used, with various sizes. Square, rectangular, and circular shapes are chosen to make up the 225 x 300 x 3000 mm column with the size of 100 mm x 100 mm, 125 mm x 150 mm, and 150 mm respectively. The first model, which is solid RC column, is named SC while the square HCRC short column is named SHC. Meanwhile, RHC and CHC are the names for rectangular and circular HCRC short column respectively.

Linear modelling is divided into a few parts such as concrete core, steel reinforcement, and interface between the two materials. Each material's properties, such as its elastic modulus, Poisson's ratio, and density, are assigned on their own. The values are shown in Table 1. The columns, shear links, and reinforcements sections act independently; thus, they have to be created as a three-dimensional solid element in the modelling space with a deformable type so that it is able to extrude in any direction. On top of that, for concrete damage plasticity, the values are also determined beforehand. It covers the dilation angle where the value is 30.5 degree, and the shape factor is 0.666. At the same time, eccentricity is 0.1, stress parameter is 1.16, and viscosity parameter is 0.001. The elements are put together to create the matrix after each part has its material properties assigned. Mesh is set to be 10000 mesh to ensure the results are determined accurate due to its 3D model. In this research, dependent instance is chosen for all the models. Following that, the increment is set. The maximum number of increments is set to 100 where the increment size starts with 0.1 and ends with 1. Once the increment is done, the interaction must be defined. Two or more zones are chosen which interact between each other to describe the type as well as properties of the interaction.

Afterwards, the boundary condition is applied to the HCRC short column. The fixed ends are chosen in this research. Going on to the following stage, the load is applied. The load applied is treated as a concentrated load and its production is chosen under the category of "Mechanical" and it is placed at the centre of the column with the given node. The starting value for the load is 500 kN until it reaches the failure state. It then continues to the step after applying the load, where a finite element mesh is created. The technique used is structured meshing where it divides the models into a grid-like pattern. Finally, once all the steps are done thoroughly, the system equation is solved. This step is described as running the program which includes analysing RC column as well as HCRC short column to decide whether it passes or not. If by any chance it fails, all the procedures need to start from the beginning just like in the flowchart. Once the status is "Completed", the results are able to be extracted.

Once the results are out, the data analysis is determined. The results obtained are analysed to achieve failure mechanisms and structural performance. Failure mechanisms are divided into crack pattern and ductility factor. Depending on the material properties, element properties, boundary conditions, applied loads and mesh, the ductility factor is able be extracted and identified using the ABAQUS software. In ABAQUS, numerical analysis is applied where it could assess the failure pattern based on its contour colour. Meanwhile for structural performance, it is divided into three things: load-displacement behaviour,

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stress-strain relationship, and energy absorption. One of the elements that should be considered with respect to the structural performance of HCRC short column is the load displacement behaviour. In order to detect any potential problems, the performance of HCRC short column under the static load is demonstrated. This includes the stress-strain curves and energy absorption capacity.

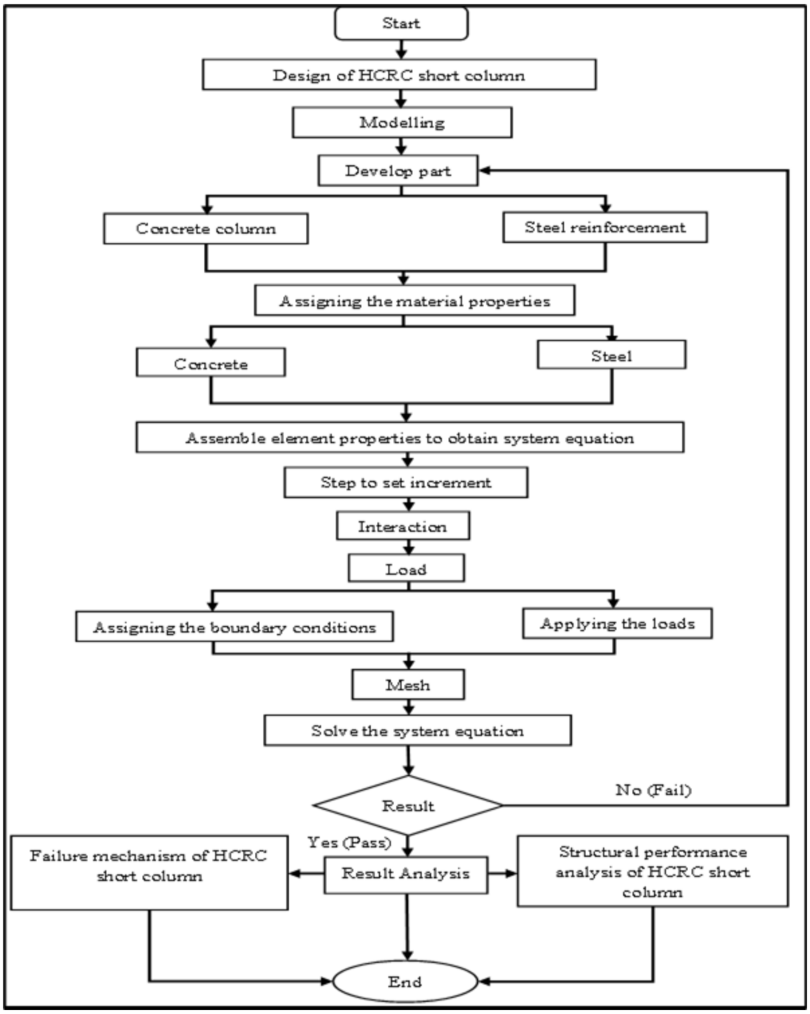

Fig 1. Overall research design

Table 1. Material properties

Material	Parameter	Value	References
Steel	Modulus of Elasticity (E)	200000 MPa	Bappy & Mostofa (2021)
	Density (ρ)	7800 kg/m^3	Bappy & Mostofa (2021)
	Poisson's Ratio (υ)	0.3	Moussa et al. (2021)
	Characteristic strength of steel (f_{yk})	500 MPa	Eurocode 3
Concrete	Modulus of Elasticity (E)	33000 MPa	Shelorkar & Jadhao (2022)
	Density (ρ)	2400 kg/m^3	Eurocode 2
	Poisson's Ratio (υ)	0.14	Eurocode 2
	Characteristic strength of concrete (f_{ck})	30 MPa	Eurocode 2

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3. RESULTS AND DISCUSSION

The information provided in this section explains how each result is obtained from the research. The explanation is provided to demonstrate that the results are accurate in the context of the objectives at the beginning of the research project. Therefore, in this section, the results are divided into two subsections: to analyse the failure mechanisms of the hollow core reinforced concrete short column under static load using finite element analysis, and to assess the structural performance of a hollow core reinforced concrete short column under static load in term of stress-strain relationship, load displacement behaviour, and energy absorption using finite element analysis.

3.1 Failure mechanism of the hollow core reinforced concrete short column under static load

Failure mechanism is one of the important factors in this research. All calculations and analysis are done to ensure that this research is able to be completed with no errors. In this HCRC short column where the static load is applied, they are able to fail in compression, buckling, shear, and bond. So, it is significant to note that a few variables, including the column dimensions, loading conditions, and design parameters are likely to have an impact on the failure mechanism of a HCRC short column. Thus, an analysis is carried out using FEA to extract the results. The displacement patterns in the study are visually represented through contour plots, where different colours indicate varying displacement values, as discussed by [13-14]. Table 2 shows a comparison of the displacement contour between four models (SC, SHC, RHC, and CHC). In the study of hollow core reinforced concrete short columns under static load, displacement patterns vary significantly with the applied load and column type. Generally, as the load increases from 500 kN to 5000 kN, displacement increases across all models, indicating greater deformation under higher loads. The solid column (SC) showed minimal displacement, ranging from 0.55 mm to 5.53 mm, demonstrating robustness. The short hollow column (SHC) exhibited moderate displacements from 1.61 mm to 9.39 mm, reflecting a more flexible response. The reinforced hollow column (RHC) displayed similar trends, with displacements of 1.07 mm to 11.22 mm. In contrast, the concrete hollow column (CHC) experienced the highest displacement, from 2.72 mm to 28.43 mm, indicating significant deformation and lower stiffness. When comparing the maximum displacement of all the models, the corresponding ratios for SC, SHC, RHC, and CHC are 3: 203: 41: 14.

The solid column (SC) demonstrates minimal displacement due to its uniform material distribution and greater overall stiffness, which allows it to better resist deformation under load. In contrast, the hollow columns, having reduced concrete volume, inherently possess lower stiffness, leading to greater displacements. As the applied load increases from 500 kN to 5000 kN, the differences in displacement among the column types become more pronounced. The gradual increase in displacement across all models indicates a consistent response to loading, with solid columns maintaining structural integrity better than hollow options. The tendency for hollow columns to exhibit sudden cracking, as noted by [15], contributes to their higher displacement values. This sudden failure mode contrasts with the more gradual cracking observed in solid columns, further emphasizing the vulnerability of hollow structures under load. The observed bending in hollow columns at higher loads highlights the importance of structural design in ensuring stability. The design of the hollow core inherently makes these columns more susceptible to buckling and crushing, which can exacerbate displacement under static loads. The conclusion that hollow columns have significantly lower stiffness compared to solid columns [16] aligns with the observed displacement trends. Lower stiffness directly correlates with higher deflection under load, which is reflected in the displacement measurements. In summary, the results are justified by the interplay of material properties, structural design, load response, and cracking behaviour, underscoring the critical need for careful consideration of these factors in engineering practices for reinforced concrete columns.

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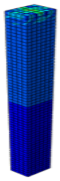
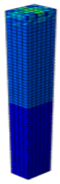
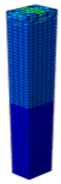
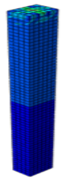
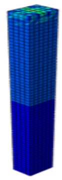
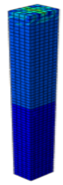
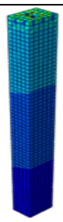
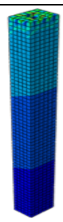
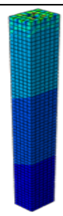
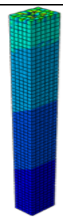
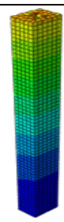
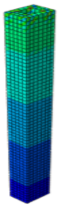
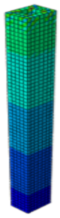
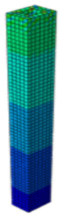
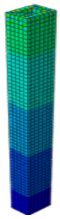
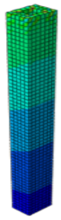
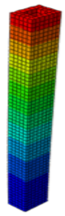
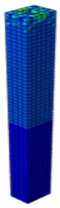
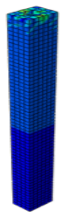
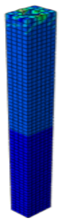
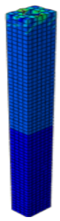
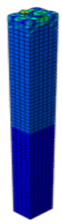
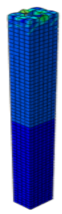
Table 2. Displacement pattern comparison of hollow core reinforced concrete short column under static load

Model	**Displacement Contour Load (kN)**					
	500	**1000**	**1750**	**2875**	**4562**	**6000**
SC						
Displacement (mm)	0.55	1.10	1.93	3.17	5.04	5.53
SHC						
Displacement (mm)	1.61	3.22	5.66	9.39	23.84	405.80
RHC						
Displacement (mm)	1.07	2.15	3.77	6.21	11.22	81.78
CHC						
Displacement (mm)	2.72	5.46	9.63	16.00	26.02	28.43

3.2 Structural performance of the hollow core reinforced concrete short column under static load

In order to achieve the objectives of this research, structural performance of the RC column is studied using FEA. The analysis is used to model the HCRC short column under static load and explain the performance of the structure in terms of load displacement behaviour, stress-strain relationship, and energy absorption of HCRC short column under static load.

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Load displacement behaviour of hollow core reinforced concrete short column under static load

Fig. 2 clearly shows the load-displacement curves of all four models. The curves are mainly divided into three parts which are elastic, plastic, and failure. Mostly, at elastic part, the curve is linear, while during the plastic part, the yield point starts. Finally, at the peak of the curve, the ultimate load capacity is found and also it shows the failure state of the column. The maximum load that all the models are able to sustain before reaching the failure state is 5000 kN. The only thing that divides them is the maximum displacement. For SC, it is 5.53 mm. Meanwhile, for SHC and RHC, they are 37.68 mm and 8.95 mm respectively. The last model, which is CHC, has a maximum displacement of 28.07 mm. The maximum displacement of hollow models is summed up using a scale with SHC being 7 times larger than SC. In the meantime, RHC is 2 times higher and CHC is 5 times higher. The relationship between the load applied to RC columns and the displacement that results from that load is known as the column's load displacement behaviour [17]. HCRC short columns operate similarly to RC columns in many ways. The load-displacement behaviour of HCRC short column is significantly influenced by the size of the hollow [18]. After applying six different values of loads to HCRC short columns, the maximum capacity is determined and used to compare with the RC column. From the results, it suggests that SC maintains the lowest displacement because of its higher cross-sectional area. The reason for this is without hollow's presence, SC has high load-bearing capacity, and it is able to withstand a large amount of load [19]. Having a high cross-sectional area is important because the area is used to resist the compressive forces acting on the column. Generally, the results show that SC is better than SHC, RHC, and CHC because it is able to withstand greater load. In research conducted by [20], solid columns have a more uniform distribution of stress, which makes them less likely to buckle under load. Nevertheless, there are several benefits to HCRC short columns over RC columns. They require less material and are lighter. The most suitable type of concrete column for a given application ultimately depends on the project's specific requirements. A solid concrete column is the superior option if load-bearing capacity is the most important factor and vice versa. Plus, RC columns are typically stiffer than HCRC short columns. As a result, they deflect less when subjected to a certain load. On the contrary, hollow-core structure deflects more under a given load because they are more flexible [21].

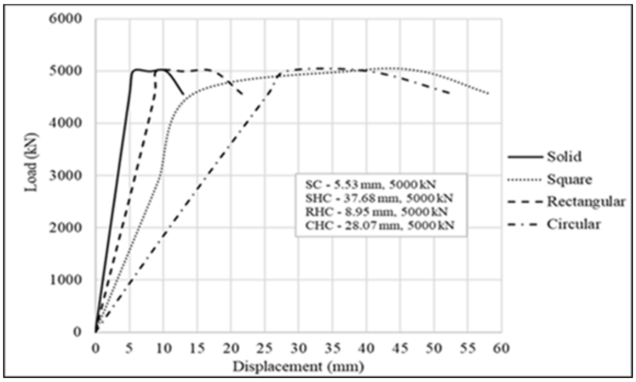

Fig. 2. Load vs. Displacement for hollow core reinforced concrete short column under static load

Stress-strain relationship of hollow core reinforced concrete short column under static load

A HCRC short column's stress-strain relationship when subjected to a static load is often nonlinear. The early linear area of the curve represents the concrete and steel's elasticity. The cross-sectional area is subjected to a maximum load of 5000 kN in the finite element analysis to show the structure's behaviour under stress and strain. The stress-strain curves for all the models are shown in Fig. 3. For the SC, the maximum stress and strain are at 732.03 N/mm^2 and 0.002029. Meanwhile for SHC, RHC, and CHC, they are able to sustain the maximum stress and strain of 1775.51 N/mm^2 and 0.005204, 3639.63 N/mm^2 and

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0.010763, and 1922.73 N/mm^2 and 0.005502, respectively. According to the results, all three models with hollow core have higher stress than the solid model. This is because the concrete inside the hollow models is not constrained by the concrete around it. This indicates that when a compressive load is applied, the concrete in the hollow core is unrestricted in its ability to expand laterally. Higher stress in the concrete is a result of this expansion [22]. The stress-strain curve becomes nonlinear as the load rises and the concrete starts to break. When the concrete reaches its compressive strength, the column reaches its maximum strength. The column keeps bending after this until it breaks [17]. The concrete strength is one of numerous factors that affects the stress-strain relationship of an HCRC short column. As the strength of the concrete increases, the stress-strain curve is going to steepen. The concrete in a solid model, on the opposite hand, is constrained by the concrete around it.

Lower stresses in the concrete are the result of this confinement, which stops the concrete from lateral expansion [23]. Between the three hollow models, RHC has the highest stress capacity due to the stress not being evenly distributed over the cross-section. As a result, the corners are more prone to bending and cracking. In a square or circular column, the corners are less vulnerable because the stress is spread more evenly. Although there are some significant changes, the stress-strain relationship of hollow columns is comparable to that of solid columns. Despite the initial stress-strain curve is linear, hollow columns have a smaller slope. This is because there is less concrete to resist the applied load thanks to the hollow core. The hollow columns start to sag as the load rises. Stress is unlikely to increase as quickly as it would in a solid column for a uniform distribution of the induced stress by the expansion of concrete, thereby reducing the stress concentration because of uneven cracking of concrete [24]. Overall, it is evident that RHC has a far higher stress-strain capacity than SC, SHC, and CHC. This is because the hollow core decreases the column's weight while maintaining the same level of lateral confinement.

As a result, concrete is capable of withstanding its maximum compressive strain before failing [25]. In addition, RHC has the smallest cross-sectional area of the three models, which causes a higher stress gradient as agreed by [26]. It means more weight has to be carried per unit area by the steel and concrete. The stress in a RHC increases at the hole's edges and reduces as it moves towards the column's centre. This concentrated high stress area has the potential for the column to fail early enough. The hollow core is not compressed, and it does not add to the column's load-bearing capacity. This indicates that the solid part of the column is bearing the load and not the hollows, which is meant to help by doing so.

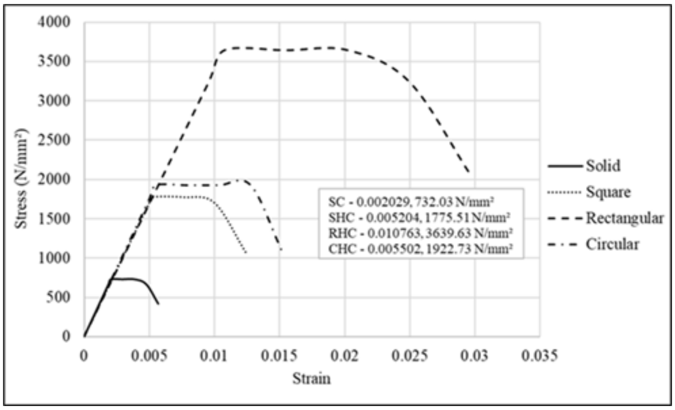

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Fig. 3. Stress vs. Strain Curves of hollow core reinforced concrete short column under static load

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Energy absorption of hollow core reinforced concrete short column under static load

Table 3 compares all four models and their corresponding energy absorption. Each model is subjected to a total of six different load values, which vary from 500 kN to 5000 kN. To calculate their energy absorption, the displacements experienced by each model are multiplied with the loads applied. Considering the highest energy absorption values for each model, SC has 27643 kN.mm and SHC has 188388 kN.mm. Meanwhile, for RHC and CHC, the values are 44738 kN.mm and 140345 kN.mm, respectively. SHC absorbs energy seven times higher than SC, while RHC is two times higher. In contrast, for CHC, it is five times higher. Based on the findings, it is concluded that all three hollow core models absorb more energy than SC. This is owing to the hollow core that allows the concrete to bend more plastically before failing, which dissipates more energy [24]. The HCRC short column is also lighter than RC column due to the hollow core. Therefore, hollow concrete columns are able to be used to sustain the same weight as solid columns while using less material during construction [20]. A column's capacity to absorb energy is affected by a variety of factors, including its material, length, and cross-sectional shape. Columns composed of brittle materials like concrete are less able to absorb energy than columns built of ductile materials like steel [27]. Generally speaking, columns with a circular cross-section have a larger capacity to absorb energy than those with square or rectangular cross-sections that may cause performance of energy dissipation [28]. Apart from that, longer columns are capable of absorbing more energy than shorter columns.

SHC has the maximum energy absorption capacity among the three hollow models because it has a higher surface-to-volume ratio. This means that SHC is unlikely to grow overly weak because there is more surface area for the concrete to deform and absorb energy. Added to that, because all four sides of the square are the same length, it is more symmetrical than either a rectangular or circular design. Due to this, the forces acting on SHC distribute more uniformly, which also helps to lessen the stress and strain placed on the concrete and cause low deformation [29]. Therefore, the study by [16] provides additional evidence for this, showing that a column with a smaller hollow cross-sectional area is going to have a higher mass and hence be able to absorb more energy. In its entirety, it is clear that compared to SC, RHC, and CHC, SHC has a far larger energy absorption capacity. The fact that it has more edges allows it to withstand higher shear force. SHC is additionally flexible than the other models. This indicates that it has a high resistance to bending and a large amount of inertia. It is advantageous because it makes it more earthquake resistant. A more flexible structure is less prone to collapse when subjected to the bending forces produced by earthquakes. It also enables it to carry a heavier load because a more flexible structure is able to bend without breaking; thus, increasing the capability of supporting greater weight. Moreover, compared to SC, RHC, and CHC, SHC has a larger torsional capacity. This is because the square hollow core resists twisting forces more effectively.

Table 3. Energy Absorption Comparison of Hollow Core Reinforced Concrete Short Column under Static Load

Models	Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
SC	Load (kN)	500	1000	1750	2875	4562	5000
	Displacement (mm)	0.55	1.10	1.93	3.17	5.04	5.53
	Energy (kN.mm)	275	1102	3376	9121	23008	27643
SHC	Load (kN)	500	1000	1750	2875	4562	5000
	Displacement (mm)	1.61	3.21	5.62	9.23	14.45	37.68
	Energy (kN.mm)	803	3212	9839	26547	65912	188388
RHC	Load (kN)	500	1000	1750	2875	4562	5000
	Displacement (mm)	0.98	1.95	3.43	5.64	8.76	8.95
	Energy (kN.mm)	488	1954	5994	16216	39962	44738
CHC	Load (kN)	500	1000	1750	2875	4562	5000
	Displacement (mm)	2.68	5.39	9.51	15.8	25.5	28.07
	Energy (kN.mm)	1341	5392	16639	45423	116350	140345

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4. CONCLUSION

The study on HCRC short columns under static load reveals significant insights into their structural performance. Notably, displacement characteristics indicate that the Square Hollow Core (SHC) model experiences the highest deformation (up to 37.68 mm), while Solid Columns (SC) exhibit minimal displacement (5.53 mm), showcasing the impact of hollow design on stiffness. Stress-strain analysis shows that HCRC columns, particularly Rectangular Hollow Core (RHC), achieve higher stress capacities (up to 3639.63 N/mm²) due to reduced lateral confinement, highlighting areas for potential failure. The energy absorption capacity of HCRC columns is markedly superior, with SHC absorbing up to 188,388 kN.mm, demonstrating its ability to undergo substantial plastic deformation before failure, crucial for resilience against dynamic loads. Load-displacement curves reveal distinct elastic and plastic phases, emphasizing the need for careful consideration of load-bearing capacities in design. Additionally, identified failure mechanisms which are compression, buckling, and shear underscore the importance of geometry and material properties in structural integrity. The successful application of FEA validates its effectiveness in modeling complex behaviours, providing reliable predictions of displacement, stress distribution, and energy absorption. Overall, these findings substantiate the potential of HCRC short columns as efficient structural elements, guiding future design methodologies and enhancing safety standards in construction applications.

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Mohd Samsudin Abdul Hamid: Conceptualisation, methodology, formal analysis, investigation and writing-original draft, supervision, writing- review and editing; **Muhammad Aidil Nordin**: Methodology, investigation, writing-original draft and formal analysis.

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