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The Behaviour of Mortar Filled Double Skin Hollow Steel Columns

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Abstract
Double Skin Hollow Mortar Filled Column (DSHMFC) is one of the composite columns that has been applied widely in civil engineering for its predominant mechanical behaviour. The hollow section in the column is to provide the space for service work such as piping and electrical conduit. These three specimens 300 mm DSHMFC columns were prepared with 65 mm, 75 mm, and 85 mm diameter of inner PVC tubes and 162.5 mm diameter of mild steel tube as outer skin. The study demonstrated the experimental investigation of DSHMFC acting as columns in compression with various diameters of the inner PVC tube. The space between the two skins was filled with mortar with a compressive strength of 42.5 MPa. The ultimate compressive load was determined in this study and compared with the theoretical values obtained from Eurocode 4. The relationship of diameter to thickness (D/t_c) ratio and the failure mechanism in DSHMFC were also observed in this study. The experimental results showed that the effective composite action of steel tubes and mortar increases the strength of DSHMFC by 95% compared to the hollow mild steel tubes. It was also observed that the failure mechanism of all the specimens was governed by local buckling. This study found the potential utilisation of PVC inner pipe as an alternative for steel in DSHMFC is feasible, especially in structures with moderate load conditions.

Keywords
Composite column; Double skin hollow mortar filled columns; Concrete filled PVC tube; Confinement effect; Local buckling

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1 Introduction

Double Skin Hollow Concrete Filled (DSHCF) column has been applied widely in civil engineering for its predominant mechanical behaviour. The column is formed by two concentric steel tubes with mortar filled in-between them. The mortar-filled double-skin steel tubular columns have high bending stiffness that avoids instability under external pressure and is lighter[1,2]. This is the most recent type of steel-mortar composite column incorporating the advantages of mortar-filled steel tubes and mortar-encased steel columns. However, this new structural element has no significant applications worldwide, partly due to the lack of understanding of their behaviour and insufficient design provisions in different design manuals[3]. The application of the

DSHCF column has gained popularity due to the significant advantages that the DSHCF column offers compared to traditional construction methods, such as it does not require formwork. Additionally, it only requires a shorter construction time, which reduces the total project completion cost. Other benefits are the interaction between steel and mortar, causing local buckling on the steel tube to be delayed by the restraint, and the strength of mortar that is increased by the confining effect provided by the steel tube.

Concrete-filled double-skinned tubes (CFDST) have collective advantages over hollow tube columns and mortar-filled tube columns. CFDST is designed by confining the mortar between two hollow steel tubes, which may vary in cross-section shape and size. This type of column has been observed to have an axial loading capacity between 10-30% more than the combined capacities of individual components. This is due to the local buckling behaviour of outer and inner steel, which was delayed due to the confining effect on the mortar. The confining effect from the steel tubes may also affect the mode of failure of concrete[4,5]. Besides, the service work application can also be applied on the double hollow column where piping and electrical conduit can be installed through the hollow section. This column can also be used for the lamp post and small load-bearing structure. Previous works on CFDST exhibit the use of various materials, including mild steel, fibre-reinforced polymer, and polyvinyl chloride (PVC) tubes[2,6-9]. The PVC tube is used because of its lighter weight, lower cost than other materials, and invulnerable to external and internal corrosion. At the same time, mild steel has high corrosion resistance and high tensile strength while being thinner. Various types of concrete used as an in-filled column are normal concrete, high-strength concrete, self-compacting concrete, and steel fibre reinforced concrete[10]. The use of high-strength concrete in the construction of new composite columns is attractive as this method could reduce the amount of rebar usage for construction. The use of self-compacting concrete was reported to reduce construction time as it eliminated the usage of vibrator machines, thus reducing the cost of machinery used[2]. CFDST construction requires high fluidity in tight joint formwork, which slows the casting rate. Therefore, utilising mortar is seen to be a feasible alternative for the in-filled material. Other parameters reported influencing the compressive strength and deflection of the columns are the length to diameter (L/D) ratio and the diameter to thickness (D/t) ratio. The diameter to thickness ratio also affects the ductility of the column[2,11].

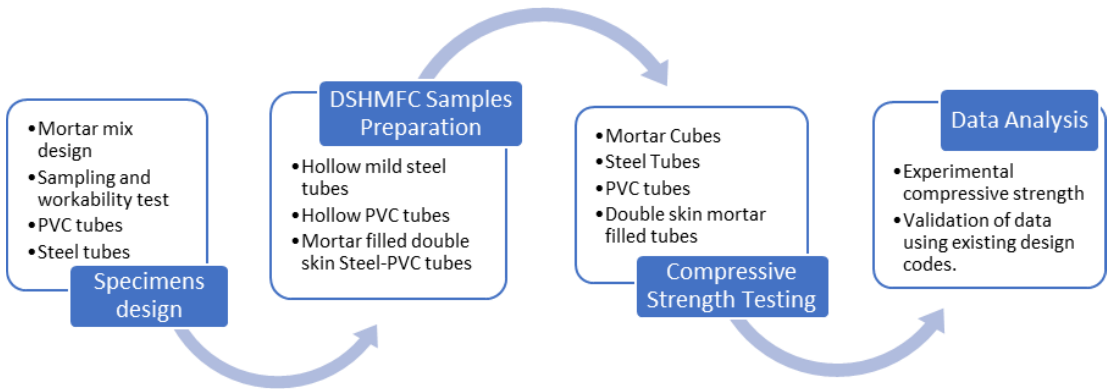

Figure 1. Methodology.

The potential utilisation of PVC inner pipe as an alternative for steel in double skin hollow column filled with mortar was investigated in this study. The behaviour of mortar-filled double-skin hollow column (DSHMFC), using mild steel tubes as the outer skin and PVC tubes with various D/t ratios as the inner skin was studied.

Table 1. Specimens' details.

Specimen	Diameter (mm)		t_c (mm)	d/t_c
	PVC	HST		
HPVC1	60	-	-	-
HPVC2	75	-	-	-
HPVC3	85	-	-	-
HST	-	162.5	-	-
DSHMFC1	60	162.5	51.3	3.2
DSHMFC2	75	162.5	42.4	3.8
DSHMFC3	85	162.5	37.4	4.3

Note: HPVC-hollow PVC tube; HST-hollow steel tube; DSHMFC-double skin hollow mortar-filled tube.

2 Experimental details

The methodology details of this study are shown in Figure 1. There are four (4) main activities in the study, namely, the design of the specimen, the sample preparation, the experimental testing, and finally, the data analysis.

A total of seven (7) specimens as shown in Table 1, were prepared, which include three (3) empty PVC labelled as HPVC1, HPVC2, and HPVC3; one (1) empty steel tube labelled as HST and; three (3) DSHMFC specimens prepared using mild steel tubes as the outer skin and PVC tubes as the inner skin labelled as DSHMFC1, DSHMFC2, and DSHMFC3.

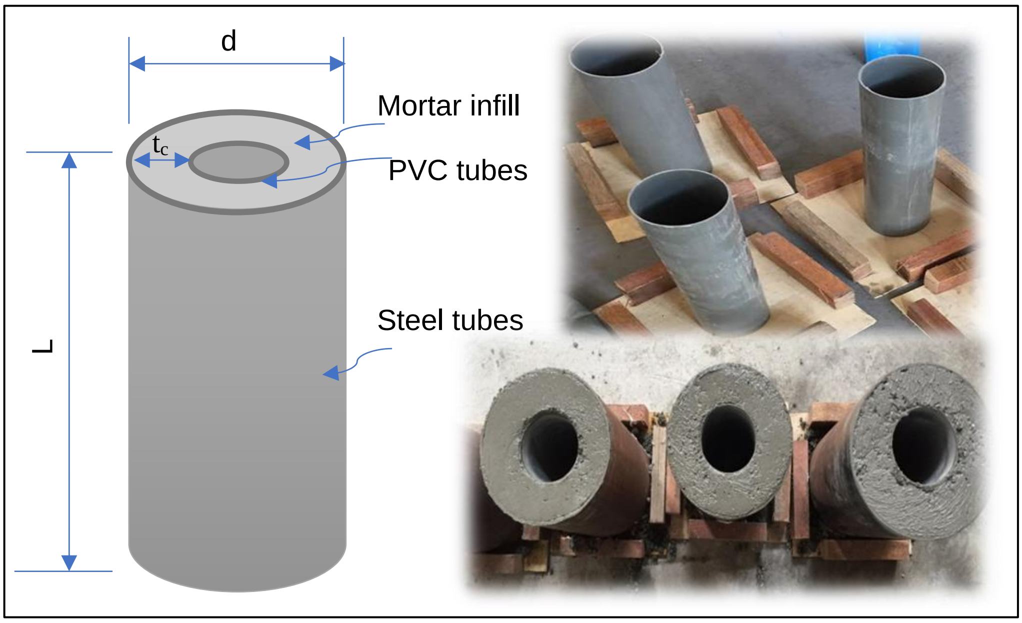

Figure 2. Double skin hollow mortar-filled columns (DSHMFC) sample preparations.

The thickness and diameter of the outer skin for these three specimens are 2.75 mm and 162.5 mm, respectively, while the diameter of the inner skin is 60 mm for DSHMFC1, 75 mm for DSHMFC2, and 85 mm for DSHMFC3 with a constant thickness of 2.75 mm. The length of all the specimens was maintained at 300 mm. The space between the two skins was filled with mortar produced with Ordinary Portland Cement.

The mortar mix was prepared with a specified water-cement ratio of 0.3 and the sand-cement ratio of 2.75. During the casting of the DSHMFC specimens, three standard concrete mortar cubes of 150 mm x 150 mm x 150 mm were prepared for each batch and placed in a curing tank for 28 days. Before the concrete casting, the PVC and the steel tubes were cut into the specified 300 mm length. The cut sections of the PVC and the steel tubes were ground to prepare a smooth cross-section and timber base plates were prepared at the bottom of the tubes. The bottom part of the PVC and steel tubes are then sealed using waterproof silicone sealant before casting, to ensure that the wet mortar does not leak out from the bottom part during casting. During casting, the space between the two skins was filled with mortar in three equal layers and carefully compacted. After casting, all the DSHMFC specimens were left at room temperature for the curing process. The schematics configuration and the DSHMFC specimens' preparations are shown in Figure 2.

Figure 3 shows the compression test and instrumentation setup for all the specimens. All the specimens were tested under axial compression load using a Universal Testing Machine with 1000 kN capacity. The compression test for DSHMFC specimens was carried out at the Heavy Lab (Structure) Laboratory, Universiti Teknolog MARA, Permatang Pauh Campus, Pulau Pinang. All the specimens were subjected to axial compression load and tested for failure. The compression test for the concrete cylinders and the concrete cubes was carried out using the Compression Testing machine and executed after 28 days of curing age. Two linear variable displacement transducers (LVDT) were used to measure the axial shortening of DSHMFC during the test, and they were placed at two sides of the specimens. Both readings at the displacement transducers were used to ensure uniform loading distribution on the cross-section of the column. The load was applied under displacement control at the rate of 0.03 mm min^{-1}.

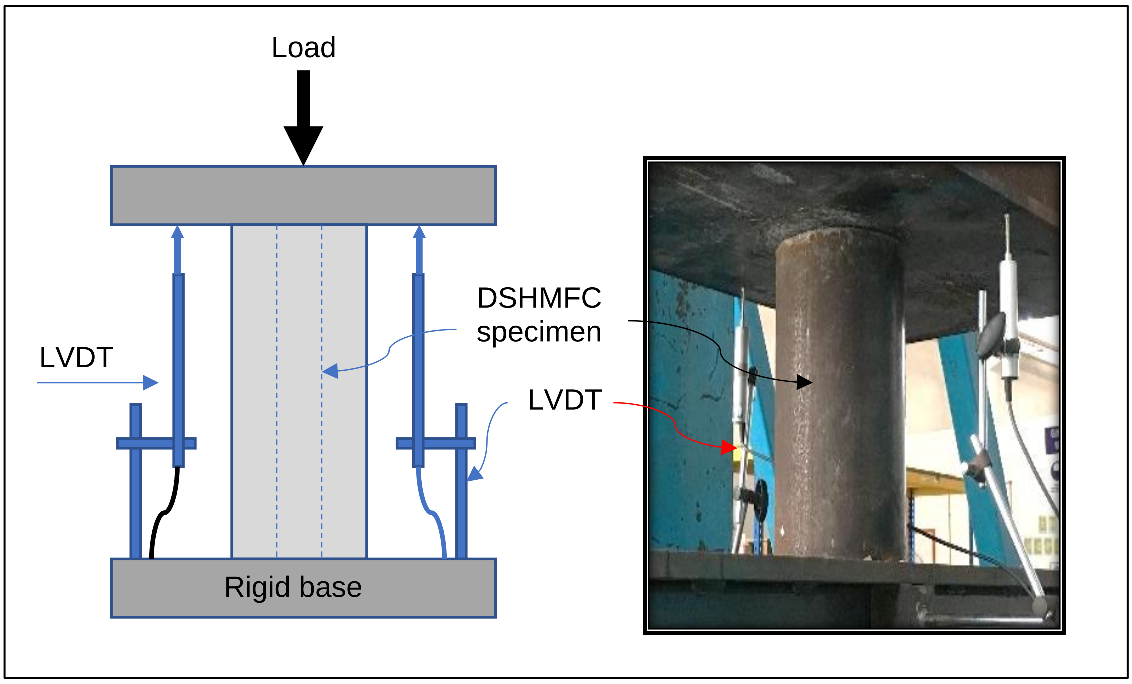

Figure 3. Compression test setup and instrumentations of DSHMFC specimens.

The data obtained from the experimental testing were then compared with the theoretical prediction value according to the Eurocode 4 (EC4) specification as given in Equation 1.

$$N_{pl,Rd} = A_a f_{yd} + 0.85 \cdot A_c f_{cd} \tag{1}$$

where $N_{pl,Rd}$ is the plastic resistance to compression of composite cross-section, A_a is the cross-sectional area of the structural PVC section, f_{yd} is the design value of yield strength of structural PVC, A_c is the cross-sectional area of a cross-section of mortar, and f_{cd}, is the design value of the cylinder compressive strength of mortar correspondingly. For mortar-filled sections, the coefficient 0.85 may be replaced by 1.0 to incorporate the confinement effect into the mortar-infilled[12].

Table 2. Ultimate compressive load of DSHMFT specimens recorded at 28 days.

Specimen	Diameter, mm		$f_{yd,}$ steel	f_{cd} Mortar	t_c (mm)	d/t_c	N_{exp} (kN)	N_{EC4} (kN)	N_{exp}/N_{EC4}
	PVC	HST							
HPVC1	60	-	-	-	-	-	7.2	-	-
HPVC2	75	-	-	-	-	-	10.5	-	-
HPVC3	85	-	-	-	-	-	13.7	-	-
HST	-	162.5	132	-	-	-	400.5	-	-
DSHMFC1	60	162.5	132	42.5	127.0	1.3	780.6	1187.50	0.65
DSHMFC2	75	162.5	132	42.5	38.3	4.2	721.1	1119.98	0.64
DSHMFC3	85	162.5	132	42.5	33.3	4.9	671.0	1065.89	0.63

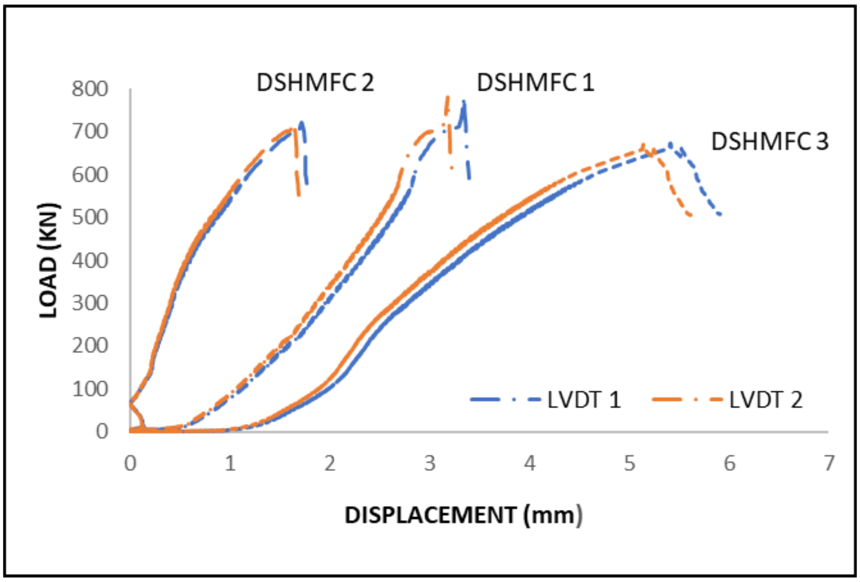

Figure 4. Axial load-displacement for DSHMFC specimens.

3 Results and Discussion

Table 2 presents the results of the recorded ultimate compressive load of all the specimens in this study. From the experimental result, the average compressive strength obtained from the mortar cubes was recorded as 42.5 MPa. The maximum load for the hollow PVC specimens was recorded at 7.2 kN, 10.5 kN, and 13.7 kN for PVC hollow tube specimens with the outer diameter of 60 mm, 75 mm, and 85 mm, respectively. Meanwhile, the maximum load for the hollow mild steel tubes was recorded at 400.5 kN.

The experimental results for the DSHMFC specimens showed a significant increase in maximum load capacity as compared to the hollow mild steel tube specimen. However, the compression strength of DSHMFC decreases with decreasing d/t_c. The maximum load for the DSHMFC was recorded to be 780.6 kN, 721 kN, and 671 kN for specimens with an inner skin of 60 mm, 75 mm, and 85 mm, respectively. These observations indicate that an increase in the inner diameter, resulted in a reduction of the cross-sectional area of mortar, thus decreasing the ultimate compressive load of the column. Figure 4 shows the axial-displacement behaviour of the DSHMFC specimens. The failure for specimens DSHMFC2, DSHMFC1, and DSHMFC3 occurred at the displacement of 1.65 mm, 3.34, and 5.56 mm, respectively. This marked the onset occurrence of the local buckling for all the specimens.

The theoretical analysis found that the EC4 overestimates the ultimate compressive strength capacity by 35%, 36%, and 37% for specimens with an inner skin of 60 mm, 75 mm, and 85 mm, respectively. The significant difference between the experimental result with the predicted strength capacity was due to the confinement effect of the DSHMFC, because the confinement effect in hollow inner skin from the PVC tube is less compared to the conventional solid mortar- filled tubes. Therefore, the inner tubes' contribution to the ultimate compression is almost negligible.

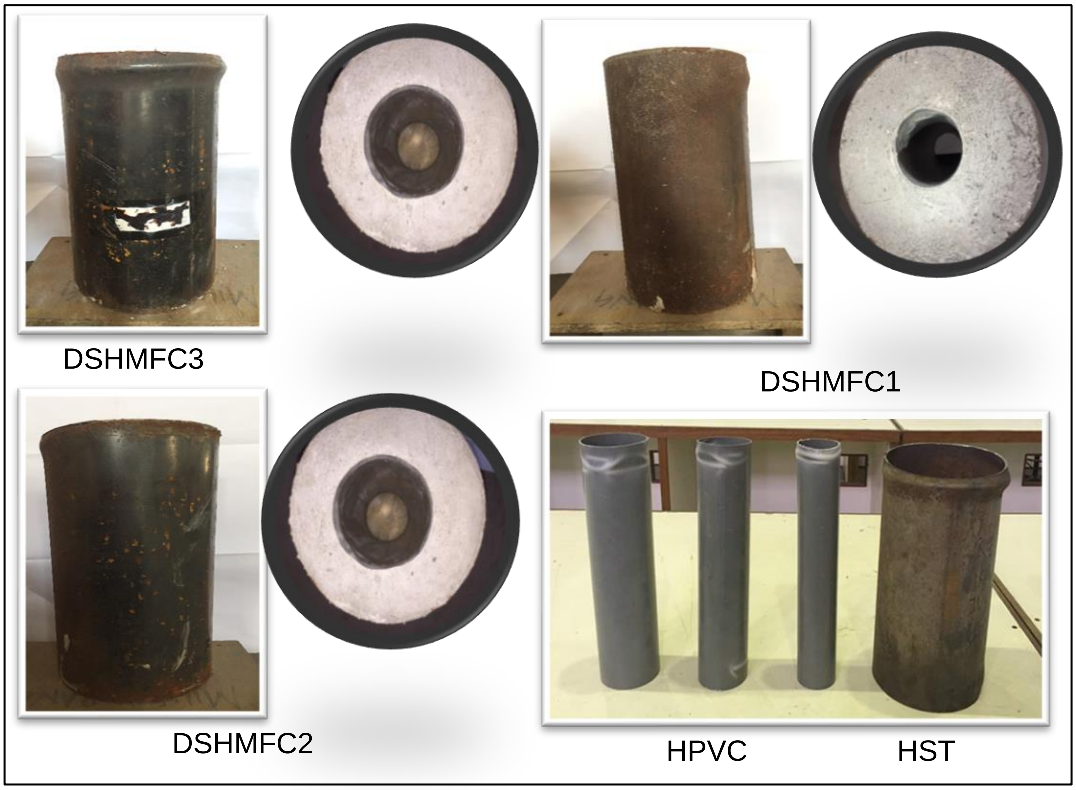

Figure 5. Failure mechanisms in DSHMFC specimens.

It was observed that all the specimens failed by local buckling located at the top edge of the specimens where the compression load was applied. The failure mechanism observed in all HPVC specimens was categorised as local buckling, which occurred inwardly at the top of all the HPVC specimens (Figure 5). Meanwhile, an outward local buckling occurred at the top edge for the empty steel tube, HST specimen. The failure mechanism for the DSHMFC specimens was observed to fail by local buckling at the top edge of the specimens. However, with the existence of mortar in-filled, the failure of column was delayed by both the steel and PVC skins that resisted the load before the whole column collapsed. This was evidenced as the DSHMFC specimens undertaking the compression test, experienced local buckling of both the steel and PVC tubes occurring at outward directions.

4 Conclusion

The feasibility of utilising PVC inner pipe as an alternative for steel in double skin hollow column filled with mortar is presented in this study. The behaviour of DSHMFC using mild steel tubes as the outer skin and PVC tubes with various D/t_c ratios as the inner skin was studied. It was found that the effective composite action of steel tubes and mortar increase the strength of DSHMFC column by 95% compared to the hollow mild steel tubes. It was also found that the compression strength of DSHMFC decreases with decreasing d/t_c due to an increase in the inner diameter, resulting in a reduction of the cross-sectional area of mortar and thus, reduced the ultimate compressive load of the column. This conclusion is similar to the results reported by Alinejad et al.[13], that the presence of PVC increases the strength capacity and ductility of the column specimens. However, the strength capacity of the column decreases by the increment of the column diameter.

The theoretical analysis found that the EC4 overestimates the ultimate compressive strength capacity by 35%, 36%, and 37% for specimens with an inner skin of 60 mm, 75 mm, and 85 mm, respectively. The significant difference between the experimental result with the predicted strength capacity was due to the confinement effect of the DSHMFC, which is less in hollow inner skin from the PVC tube compared to the conventional solid concrete-filled tubes. Therefore, the inner tubes' contribution to the ultimate compression is almost negligible.

The failure mechanism of all the specimens was governed by local buckling, which is favourable in the construction industry. Therefore, the potential utilisation of PVC inner pipe as an alternative for steel in DSHMFC is found to be feasible for moderate load conditions. It is recommended that further investigation, should be conducted to understand the behaviour of the confinement effect of the inner skin and to formulate a reliable prediction model for the compressive strength capacity.

Conflict of Interest

The author declares that there is no conflict of interest.

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Data curation: Petrus, C., & Let, Z.
Methodology: Goh, L.D., & Let, Z.
Formal analysis: Petrus, C., & Goh, L.D
Visualisation: Let, Z.
Software: Not applicable
Writing (original draft): Petrus, C., & Let, Z.
Writing (review and editing): Petrus, C., & Goh, L.D.
Validation: Petrus, C.
Supervision: Petrus, C., & Goh, L.D.
Funding acquisition: Petrus, C.
Project administration: Petrus, C.

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