

Review

Review of the Short-Term Properties of Confined Seawater Sea Sand Concrete Columns under Compression

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Abstract: The environmental concerns raised by the over-exploitation of fresh water and river sand have driven researchers to explore seawater sea sand concrete (SWSSC) as a substitute for conventional concrete in structural columns. With numerous investigations on this in the past, there is a need to systematically classify and comprehensively understand the response of confined SWSSC columns to promote their usage as structural columns. Consequently, the objective of this review is to summarise and analyse the experimental work conducted so far on confined SWSSC under different compressive loadings. Confined SWSSC columns are classified into five confinement schemes based on the cross-section of the specimens: single-skin, single-skin multilayered, single-skin with additional reinforcement, double-skin, and double-tube-confined SWSSC columns. Based on the findings of the reviewed studies, it can be concluded that the compressive strength and the ductility of the SWSSC can be enhanced through confinement, with effectiveness majorly depending on the material and geometrical properties of the confinement providing material. The existing research work on SWSSC confinement lays out a strong base for future investigations in this area, which will eventually facilitate the acceptance of SWSSC as structural columns, especially for coastal and marine infrastructure.

Keywords: seawater sea sand concrete; confinement; strengthening; fibre-reinforced polymer; stainless steel; compressive behaviour



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1. Introduction

The requirement for new infrastructure increases parallelly with the rapid growth in population and urbanization. To satisfy this need, the construction industry produces a tremendous amount of concrete every year. In 2020, about 14 billion cubic metres of concrete was produced in the world [1]. The increasing usage of concrete has resulted in the extraction of huge amounts of conventionally used fresh water and river sand from nature. As a result, this exploitation of natural resources has created environmental concerns amongst researchers on a global level.

Although 71% of the earth's surface is covered with water, shortage of fresh water is still a major problem across various countries. In 2020, around 3.2 billion people across the world lived in water-stressed countries [2]. Due to its abundance on earth, seawater as a replacement for conventionally used fresh water has the possibility to sustainably manage available water resources on earth. With the rising demand for concrete, the mining of river sand for its use as fine aggregates has also drastically risen, and this is accountable

for damaging the river ecosystem. Excessive extraction of river sand triggers degradation of riverbed which can induce change in direction of river flow and impacts the associated biodiversity. As a result, strict regulations have been established in several countries to stop excessive river sand mining, and this has led to a substantial increase in the price of river sand [3]. Sea sand could be used in concrete as an alternative to the conventionally used river sand to meet the demands of construction industry. As required, this will result in the preservation of the river ecosystem. Because of the environmental benefits provided by the usage of seawater and sea sand, researchers have been attracted by the prospects of using them as raw materials in concrete instead of conventionally used fresh water and river sand. This could be extremely feasible for the development of new coastal and marine infrastructure, where the supply of fresh water and river sand is limited and the procurement of seawater and sea sand is easier [4,5].

To further enhance the structural behaviour of concrete in columns, researchers have explored the concept of confinement. One way to do this is to fill the concrete in tubes made up of carbon steel, stainless steel, FRP, etc., usually referred to as concrete-filled tubes. Concrete filled steel tubes as a composite structural column have been successfully used as columns for high rise buildings, pile foundations and piers for bridges, and as structural members for offshore structures. The composite action of steel and concrete induces higher strength, improved ductility, and increased energy absorption capabilities [6]. Additionally, the infill concrete reduces the local buckling of the confining steel tube [7]. Furthermore, they can also act as formwork for the concrete and result in more economical construction [8]. However, if SWSSC is to be used, the commonly used carbon steel is not a good choice for providing confinement as it is widely acknowledged that the presence of chloride ions in seawater and sea sand has detrimental effects on carbon steel [5]. Therefore, non-corroding materials such as stainless steel and FRP are usually employed to provide confinement to SWSSC [9].

Retrofitting or strengthening is another form of confinement that has been very effective in restoring the structural properties of damaged or deficient concrete columns [10]. In addition to enhancing the load carrying capacity, this type of confinement can also reinstate the ductility of the column [11]. Furthermore, the rehabilitation of structures is far more sustainable than demolishing them as it supports the ideology of the conservation of natural resources [12]. The traditional retrofitting technique in the form of steel jackets is not very economical and if performed on SWSSC columns, it will lead to the corrosion of steel jackets [13,14]. Due to the excellent mechanical properties and corrosion resistance of FRP, the rehabilitation or strengthening of SWSSC conducted by utilizing it is a viable option [15].

When it comes to the confinement of SWSSC, a wide range of techniques has been investigated by researchers to date. In simple terms, they can be classified into single-skin, double-skin, and double-tube confinement schemes (Classifications A, B, and C in Figure 1, respectively). However, two more classifications are proposed which can also be considered as subsections of single-skin-confined SWSSC columns. These are represented by Classifications D and E in Figure 1. In Classification D, SWSSC columns are confined in a single-skin fashion but by more than one type of material. This results in enabling the confining shell to have more than one layer. For example, Huang et al. [16] studied the axial compressive performance of CFRP sheets wrapped stainless steel tubes filled with SWSSC. This type of confinement scheme will be referred to as single-skin multilayered confinement. For Classification E in Figure 1, SWSSC columns are again confined in a single-skin fashion with extra reinforcements. This confinement scheme will be referred to as single-skin confinement with additional reinforcement. All five of these confinement classifications are discussed in Section 4 of this paper. It should be noted that usage of additional reinforcement has not been studied with double-skin- or double-tube confined SWSSC columns.

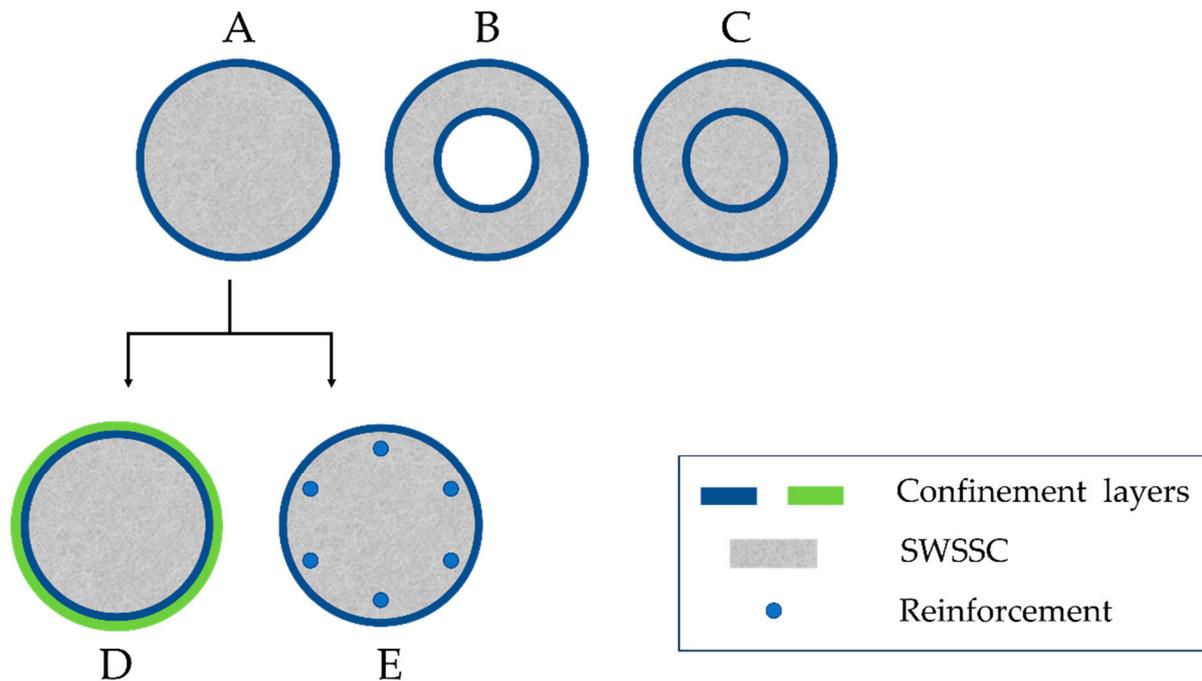


Figure 1. Cross sections of studied confinement schemes of SWSSC columns in literature ((A): single-skin, (B): double-skin, (C): double-tube, (D): single-skin multilayered, and (E): single-skin with additional reinforcement).

This study presents an overview of the existing literature on the short-term compressive studies of various SWSSC filled tubes and strengthened/wrapped SWSSC columns along with some direction for future investigations. Majority of the studies on confined SWSSC have focused on concentric axial compression loading. Only a few researchers have studied the effects of eccentric axial compression and cyclic axial compression loading on confined SWSSC. Studies on all of the aforementioned loading conditions are considered in this paper. A total of 47 articles based on short-term compressive performance of confined SWSSC were reviewed, and key attributes, including materials used to provide confinement and studied confinement schemes, were selected. These are shown in the research framework designed for this study shown in Figure 2. The review study was conducted using the following research methodology. Reputable databases were searched for research articles, conference papers and review papers in the year range of 1990 to 2023 with appropriate keywords such as “confined seawater sea sand concrete”, “confined marine concrete”, and “FRP confined seawater sea sand concrete”. A database using a spreadsheet was then created with title, publication year, loading type, confinement scheme studies, and material used for confinement as objects.

Although the concept of SWSSC is not recent, its usage in structural columns is not as widespread as conventional concrete. Furthermore, the existing review study in the field of confined SWSSC does not encompass all the confining materials used so far. Consequently, it was deemed necessary to review and consolidate the pre-existing literature on confined SWSSC columns. The outcome of this review will provide a sound knowledge base for further studies on confined SWSSC columns, which will eventually aid in bridging the gap between research and practical application of confined SWSSC columns.

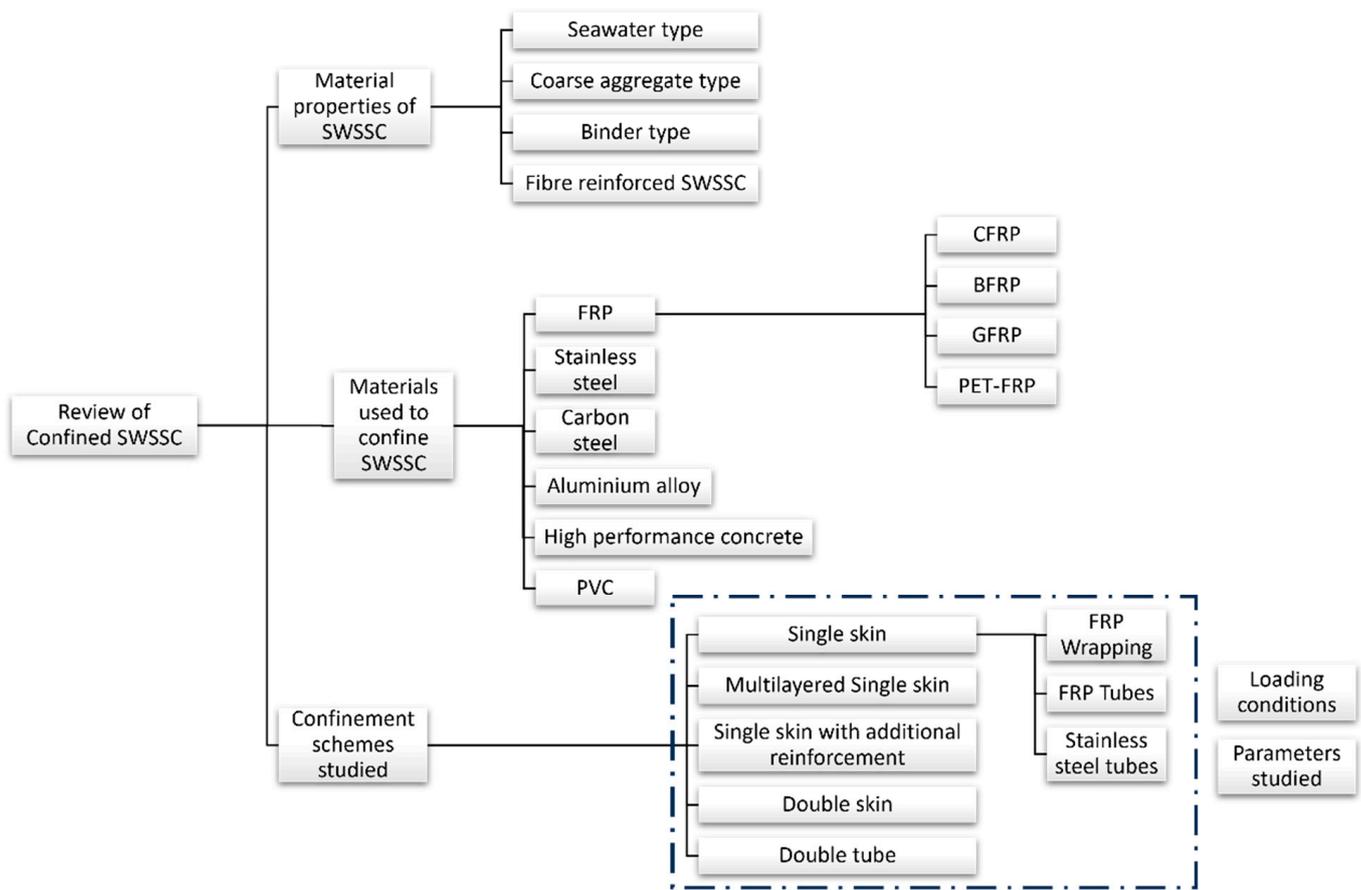


Figure 2. Research framework for this study.

2. Properties of SWSSC Used in Confinement Studies

The inclusion of seawater and sea sand in concrete has gained popularity amongst researchers in the past few decades because of the better sustainability perspective they can offer. Furthermore, it is well agreed that compared to conventional concrete made from fresh water and river sand, SWSSC shows early high strength because of the faster initial hydration of cement paste due to the presence of dissolved salts and a relatively higher pH of seawater [17]. This makes SWSSC suitable where a rapid pace of construction is required. When it comes to the long-term strength of SWSSC, some variations have been observed when it is compared to conventional concrete. In some of the research conducted, the long-term compressive strength of seawater and/or sea sand concrete was found to be equal or higher than the conventional concrete [18,19], whereas contrasting results were observed in some of the studies as the compressive strength of SWSSC was slightly lower than the conventional concrete [4,20]. Moreover, in a review of 85 studies, more than half reported that concrete made from seawater is superior to conventional concrete [21]. One reason for this discrepancy is the varying composition and properties of seawater and sea sand found in different geographical locations [18]. The mix proportion used to make SWSSC also has significant effect on its fresh and hardened properties [22]. Furthermore, the addition of mineral admixtures such as fly ash and blast furnace slag also has the potential to enhance the compressive and tensile strengths of SWSSC [3,23]. The properties of SWSSC used in confinement studies are summarised in Table 1

Table 1. Material characteristics of the SWSSC used in the confinement studies.

Reference	Binder	Seawater Type	Aggregates	Water to Binder Ratio	Compressive Strength (MPa)	Confinement Scheme Studied
[24]	AAS	Natural SW	Ordinary aggregates	0.53	32.8 * to 39.4 *	SS and DS
[25]	AAS	Natural SW	Ordinary aggregates	0.53	31.4 *	SS and DS
[26]	AAS	Natural SW	Ordinary aggregates	0.53	42 *	SS and DS
[27]	AAS	Natural SW	Ordinary aggregates	0.53	29.8 * to 39.4 *	SS and DS
[9]	AAS	Natural SW	Ordinary aggregates	0.53	28.7 * and 29.9 *	SS and DT
[28]	OPC	Natural SW	Coral aggregates	0.49	42.1 *	SS and SSM
[29]	OPC	Natural SW	Ordinary aggregates	0.43	40.5 #	SS
		Artificial SW			39.1 #	
[30]	OPC	Artificial SW	Coral aggregates	0.55	18.6 *	SS and SSwAR
[31]	OPC	Artificial SW	Ordinary aggregates	0.54 and 0.4	34.16 # and 46.86 #	DT
[32]	OPC	Artificial SW	Coral aggregates	0.55	18.6 *	SS and SSwAR
[33]	OPC	Artificial SW	Ordinary aggregates	0.54	52 *	SS and SSM
[34]	OPC	Natural SW	Ordinary aggregates	0.51	36.4 †	SS and SSM
[35]	OPC	Natural SW	Ordinary aggregates	0.49	51.0 † and 31.3 *	DT
[36]	OPC	Natural SW	Ordinary aggregates	0.49	45.1 *	SS and SSM
[37]	OPC	Natural SW	Ordinary aggregates	0.50	66.8 † to 35.8 † (at −60° to 20°)	SS
[38]	OPC	Natural SW	Recycled aggregates	0.50	36.5	DS
[39]	OPC	Natural SW	Ordinary aggregates	0.56 and 0.32	31.25 * and 75 *	SS
[40]	OPC	Natural SW	Ordinary aggregates	0.31	64 *	SS and SSM
[41]	OPC	Artificial SW	Ordinary aggregates	0.38	40.3 *	SSwAR
[42]	OPC	Natural SW	Ordinary aggregates	0.49	43.8 *	SS and SSM
[43]	OPC	Natural SW	Ordinary aggregates	0.43	39.14 *	SS
[44]	OPC	Artificial SW	Coral aggregates	0.78	59.02 †	SS
[45]	OPC	Natural SW	Ordinary aggregates	0.35	55.1 *	SS
			Coral aggregates	0.55	41.7 *	
			Coral aggregates with BFRP needles	0.55	38.7 *	
[46]	AAS	Natural SW	Ordinary aggregates	0.53	46.2 *	SS
[47]	OPC	Natural SW	Ordinary aggregates	0.48	44.6 *	SS
[48]	OPC	Natural SW	Ordinary aggregates	0.58	32.81 *	SS
[49]	OPC	Natural SW	Ordinary aggregates	0.58	36.25 #	SS
[50]	OPC	Natural SW	Ordinary aggregates	0.58	32.8 *	SS
[51]	OPC	Natural SW	Ordinary aggregates	0.58	36.3 #	SS
[52]	OPC	Natural SW	Ordinary aggregates	0.58	34.8 *	SS and SSwAR
[16]	OPC	Artificial SW	Ordinary aggregates	0.49	34.1 *	SS and SSM
[53]	OPC	Artificial SW	Ordinary aggregates	0.55 and 0.26	52 * and 89.7 *	SS and SSM
[54]	OPC	Artificial SW	Ordinary aggregates	0.49	34.9 *	SS and DT
[55]	OPC	Natural SW	Coral aggregates	0.50	37.25 † and 27.09 #	SS and SSM
[56]	OPC	Natural SW	Coral aggregates	0.49	42.1 *	SS and SSM

Table 1. Cont.

Reference	Binder	Seawater Type	Aggregates	Water to Binder Ratio	Compressive Strength (MPa)	Confinement Scheme Studied
[57]	OPC	Natural SW	Ordinary aggregates	0.41	44.2 [†] and 34.9 [*]	SS and SSM
[58]	OPC	Natural SW	Ordinary aggregates	0.41	49.5 [†]	SS and SSM
[59]	OPC	Natural SW	Sea stone	0.43	51.08 [†]	SS, DT and SSwAR
[60]	OPC	Artificial SW	Ordinary aggregates	0.47	35.8 [†]	SSwAR
			Recycled aggregates	0.47	37.7 [†]	
[61]	OPC	Natural SW	Coral aggregates	0.50	≈45 [†]	SS
	OPC	Natural SW	Coral aggregates and SPF	0.50	≈55 [†] to 63 [†]	
[62]	OPC	Natural SW	Coral aggregates	0.48	31.5 [†] and 27.8 [#]	SS and SSwAR
[63]	OPC	Artificial SW	Ordinary aggregates	0.46	37.7 [*] (Normal casting)	SS
				0.46	52.2 [*] (Compression casting)	
				0.46	52.2 [*] (Compression casting)	
[64]	OPC	Natural SW	Recycled aggregates	0.50	-	SS
[65]	OPC	Artificial SW	Recycled aggregates	0.37 and 0.51	32.82 and 47.98	SS and SSM

Note: * refers to compressive strength of cylinders, [†] refers to compressive strength of cubes, [#] refers to compressive strength of prisms, SS refers to single-skin, DS refers to double-skin, DT refers to double-tube, SSM refers to single-skin multilayered, SSwAR refers to single-skin with additional reinforcement, and “-” refers to data not available.

As summarised in Table 1, naturally available coarse aggregates have been employed in majority of the studies focusing on confined SWSSC. However, in some of the studies, coral aggregates and recycled coarse aggregates have also been utilised. Usage of coral aggregates makes SWSSC further economical for marine infrastructure as the cost of transportation of natural aggregates can be averted. However, when compared with naturally available aggregates, coral aggregates are lightweight due to their porous structure and have high chloride contents. Lower density leads to lower compressive strength of concrete, and high salt content promotes hydration rate [66]. They also have a significantly higher water absorption rate and a rougher surface. As a result, more water is required to achieve higher compressive strength and workability [67]. Table 2 summarises the properties of coral aggregates used by researchers in studying confined seawater sea sand coral aggregate concrete (SWSSCAC). For the sake of comparison, the bulk density and water absorption of gravel in one of the studies were 1572 kg/m³ and 1.2%, respectively [62]. Coral aggregates during the initial stage of mixing absorb extra water, resulting in reduced local water-to-binder ratio, and this absorbed water is later released during the hydration process, resulting in the formation of a denser interfacial transition zone between the cement phase and aggregates [68].

By using recycled coarse aggregates as aggregates in SWSSC, sustainability perspective can be additionally enhanced. Through this, further exploitation of natural aggregates can be prevented, and this practice also facilitates a superior solution to the disposal of demolished concrete structures. However, concrete made with recycled aggregates is associated with inferior mechanical properties. This is because of the high porosity of the old interfacial zone adhered to the recycled aggregates resulting in increased water absorption [69,70]. The inferiority in mechanical properties of SWSSC with coral aggregates or recycled aggregates can be potentially minimized by using confinement.

Table 2. Bulk density and water absorption of coral aggregates used in studying confinement of SWSSCAC.

Reference	Bulk Density (kg/m ³)	Water Absorption (%)
[28]	920	-
[44]	978	11.2
[55]	1009	11.86
[61]	1009	11.86
[62]	971	13.2

Note: “-” refers to data not available.

In addition to the commonly used ordinary Portland cement (OPC) as the binder material, alkali-activated slag has also been used in some of the studies. Furthermore, many studies on confined SWSSC have adopted artificial or simulated seawater instead of naturally available seawater. The process to synthesise artificial seawater is specified in ASTM D1141 [71]. Very limited researchers have investigated the effect of confinement on high strength SWSSC having a control compressive strength of more than 60 MPa. Few researchers have also investigated the confinement of fibre reinforced SWSSC by using BFRP needles [45] and structural polypropylene fibres (SPF) [61]. BFRP needles with a length of 100 mm and a diameter of 10 mm were produced from cutting BFRP bar scraps and were used to replace coarse aggregates. However, the compressive performance of control SWSSC made with BFRP needles was inferior due to the poor interlocking as they were cylindrical in shape. Structural polypropylene fibres used by Sun et al. [61] were 30 mm long and had a diameter of 0.6 mm. With increasing amount of SPF from 4 to 6 kg/m³, the compressive performance of control concrete increased from 19.4% to 36.8%. It is worth mentioning that the effects of steel fibres and stainless steel fibres have not been explored for confined SWSSC columns. Furthermore, carbon and aramid fibres have been used in conventional concrete to enhance their properties [72]. However, their usage in confined SWSSC is also unexplored.

The effect of compression casting technique on confined SWSSC was investigated by Yuan et al. [63]. By applying a compressive stress of 15 MPa for 2 min on freshly mixed concrete through a special casting device, the compressive strength and density of control SWSSC were improved by 38% and 7%, respectively. However, with the increasing strength of compression casted SWSSC, the brittleness was also found to be increased. The effect of low temperature on confined SWSSC was investigated by Xie et al. [37] to facilitate their usage in arctic areas. It was observed that the compressive behaviour of control SWSSC was improved by up to 90% for reduced temperatures.

3. Materials Used to Confine SWSSC

Although SWSSC has the potential to facilitate sustainability and possesses some enhanced mechanical properties as compared to conventional concrete, the presence of chloride ions promotes the corrosion of carbon steel if used as internal or external reinforcement with SWSSC [73]. Consequently, alternative materials with anti-corrosive behaviour are preferred to confine SWSSC. So far, a variety of materials have been explored by the researchers to provide confinement for SWSSC. The vast majority of these studies has focussed on FRP and stainless steel as they offer excellent corrosion resistance. However, a few researchers have also utilised comparatively inferior materials such as carbon steel, poly vinyl chloride (PVC), and aluminium alloy. All these materials are discussed subsequently.

3.1. Fibre Reinforced Polymer

Based on the review conducted on different materials employed in confining SWSSC, FRP composites are the most used due to the favourable material properties offered by them. Owing to the high durability and resistance to corrosion, FRP needs much less maintenance. It also offers a high strength-to-weight ratio when compared to metals, which results in

the reduction of the overall weight of the structure as less material is required. This will lead to more economical construction. In addition to providing increase in compressive strength, FRP also induces superior ductility to the confined SWSSC specimens due to its outstanding tensile properties. Furthermore, they also offer great electromagnetic transparency and easy recyclability. However, FRP is also associated with high initial costs and vulnerability to fire [74–76]. Depending on the type of fibre used, FRP composites can be commonly classified as carbon fibre reinforced polymer (CFRP), basalt fibre reinforced polymer (BFRP), glass fibre reinforced polymer (GFRP), aramid fibre reinforced polymer (AFRP), and polyethylene terephthalate fibre-reinforced polymer (PET-FRP) [77]. Amongst these, CFRP, BFRP, GFRP, and PET-FRP have been used by researchers so far to confine SWSSC. No study exists on the usage of AFRP along with SWSSC. This could be because of the poor compressive strength, low long-term strength, and the challenging procedure of cutting and processing [76].

When it comes to the confinement of SWSSC, FRP has been utilised in the form of premanufactured tubes and wrapping/jacketing. In the former, SWSSC is filled inside premanufactured FRP tubes, whereas in the latter, a certain number of FRP sheets are wrapped throughout the shaft of the SWSSC column. The premanufactured FRP tubes can be made by filament-winding and pultrusion processes, and both result in the distinct mechanical properties of the FRP tubes. In pultruded FRP tubes, the fibres are aligned in only the longitudinal direction, resulting in high strength longitudinally, whereas in filament-wound FRP tubes, fibres are aligned in the axial as well as the hoop/lateral direction. The fibres present in the hoop/lateral direction have the ability to restrain the lateral expansion of SWSSC when axial load is applied [78]. For this reason, filament-wound tubes were the major attraction for researchers for SWSSC filled FRP tubes. In some of the studies, FRP tubes used to confine SWSSC were made on site by wrapping FRP sheets on cylindrical moulds, referred to as in-situ-made tubes.

Table 3 summarises the properties of various FRP tubes utilised to confine SWSSC. It can be observed that FRP tubes have been used in all five types of confinement schemes mentioned in Section 1 of this paper. Furthermore, the majority of researchers have used GFRP tubes for their investigations. A wide range of diameter-to-thickness ratios ranging from 16 to 78.61 have been investigated by researchers so far. Furthermore, FRP tubes with circular cross sections have been the choice for the vast majority of researchers. The fibre volume fraction of the tubes ranged from 48% to 68%, and the fibres were also inclined at varying angles. It is well established that the effectiveness of confinement provided by FRP tubes depends on the diameter-to-thickness ratio, fibre volume fraction and the direction of fibre alignment [74]. These properties govern the behaviour of SWSSC filled FRP tubes. Typically, hoop direction properties of the FRP tubes are usually measured using the split-disk test, and the tensile properties are measured through the tensile coupon test [79]. To find out about the compressive strength of FRP tubes, axial compressive tests on their hollow sections are performed. In the compressive strength test on hollow filament-wound FRP tubes, it was observed that their failure mode is local buckling at the ends. As a result, a drop in load occurs, but the FRP section still shows residual strength [24,25].

FRP in the form of sheets or jackets have also been used to confine or strengthen SWSSC columns. As of now, CFRP, BFRP, and PET-FRP are three different types of FRP sheets that have been used for this purpose. Table 4 summarises the properties of the FRP sheets conducted via tensile coupon testing from different researchers. It can be seen that the tensile strength of CFRP is the highest, followed by BFRP and then by PET-FRP. This shows that CFRP is the most suitable material for providing confinement to SWSSC when maximum enhancement in load-carrying capacity is needed. On the other hand, the tensile rupture strain of PET-FRP is the highest, followed by BFRP and then by CFRP. Because of this, PET-FRP is the most suitable material for confining SWSSC when maximum deformation capacity is required. Amongst different types of FRP sheets used, CFRP has been used the most, and very few studies have focused on BFRP and PET-FRP sheets. Even though GFRP sheets have not been used to confine SWSSC, their tensile strength is usually

less than CFRP but higher than BFRP. Whereas their tensile rupture strain is less than PET-FRP [80]. FRP sheets have been used in all five classifications of confinement, however, vast majority of the researchers have studied single-skin and single-skin multilayered confinement schemes through them. It should be noted that FRP sheets in a double-tube confinement scheme were used alongside PVC tubes (i.e., CFRP sheets were wrapped on PVC tubes, and the composite tube acted as an inner tube).

Table 3. Properties of various FRP tubes used in the literature to confine SWSSC.

Reference	Shape	Tube Type	Manufacturing Process	Fibre Volume Fraction	Orientation of Fibres	Diameter or Side (mm)	Diameter-to-Thickness or Side Ratio	Confinement Scheme Studied
[24]	Circular	CFRP	Filament winding	60%	20%, 40%, and 40% fibres at angles of 15°, ±40°, and ±75°	50.5 to 158.1	17.97 to 56.67	Single-skin and double-skin (as inner and outer tube)
		BFRP				50 to 157.7	18.45 to 58.19	
[25]	Circular	GFRP	Filament winding	-	20%, 40%, and 40% fibres at angles of 15°, ±40°, and ±75°	51.1 to 158.3	16 to 54.11	
[27]	Circular	GFRP	Filament winding	-	20%, 40%, and 40% fibres at angles of ±15°, ±40°, and ±75°	51.1 to 158	16.64 to 50.32	Single-skin and double-skin (as inner and outer tube)
		CFRP				50.5 to 158	17.97 to 56.63	
		BFRP				50 to 158	18.45 to 58.3	
[9]	Circular	BFRP	Filament winding	-	20%, 40%, and 40% fibres at angles of 15°, ±40°, and ±75°	50 to 158	18.45 to 58.3	Single-skin and double-tube (as inner and outer tube)
		CFRP				99.9	35.55	Double-tube (as inner tube)
[30]	Circular	BFRP	In situ	-	±67.5°	150	31.91 and 65.22	Single-skin and single-skin with additional reinforcement
[32]	Circular	BFRP	In situ	-	±67.5°	150	42.86 and 65.22	
[31]	Circular	GFRP	-	-	-	106 to 158	34.19 to 51.49	Double-tube (as inner tube)
[37]	Circular	GFRP	Filament winding	68%	40% and 60% at angles of ±80° and ±60°	100 to 200	20 to 50	Single-skin
[44]	Circular	GFRP	Filament winding	48%	40% and 60% at angles of ±80° and ±60°	300	42.42 to 78.61	Single-skin
[45]	Circular	GFRP	Filament winding	65%	±63°	150	37.5 and 50	Single-skin
[61]	Circular	GFRP	Filament winding	-	±70°	130	32.5 to 65	Single-skin
[62]	Circular	GFRP	Filament winding	55%	±80°	200	33.33 to 50	Single-skin with additional reinforcement
[55]	Circular	GFRP	Filament winding	-	±70°	127 to 133	31.75 to 66.5	Single skin multilayered
[46]	Square	GFRP	Filament winding	-	20%, 40%, and 40% fibres at angles of ±15°, ±40°, and ±75°	53.1 and 55.6	19.86 and 32.58	Single-skin
		CFRP				53.4 and 56	18.54 and 33.58	
		BFRP				53.4 and 56.3	17.76 and 31.05	

Note: “-” refers to data not available.

Table 4. Properties of FRP sheets used in the literature to confine SWSSC.

References	FRP Type	Nominal Thickness of FRP Sheet (mm)	Tensile Strength (MPa)	Tensile Rupture Strain (%)	Average Elastic Modulus (GPa)	Confinement Scheme Studied
[28]	CFRP	0.167	3475.9	1.42	243.5	Single-skin multilayered
	BFRP	0.167	1673.6	2.36	71.1	
[29]	PET-FRP	0.841	770	9.39	19 and 7.3	Single-skin (full wrapping)
	CFRP	0.167	4308.6	1.81	238.3	
[31]	CFRP	0.167	3543	1.74	243	Double-tube
[33]	CFRP	0.167	4324.20	1.85	233.4	Single-skin multilayered
[34]	CFRP	0.167	3475.9	1.29	269.4	Single-skin multilayered
	BFRP	0.167	1673.6	2.36	71	
[36]	CFRP	0.167	3331.7	1.39	239.8	Single-skin (full wrapping) and single-skin multilayered
	BFRP	0.167	1641.8	2.22	74.3	
[38]	CFRP	0.167	3930	1.61	244	Double-skin
[40]	BFRP	0.167	1642.8	2.22	74.8	Single-skin multilayered
	CFRP	0.167	3331.7	1.39	239.8	
[42]	BFRP	0.167	1642.8	2.22	74.8	Single-skin multilayered
	CFRP	0.167	3331.7	1.39	239.8	
[43]	CFRP	0.167	4308.6	1.91	238.3	Single-skin (full wrapping)
	PET-FRP	0.841	770	9.39	18.9 and 7.3	
[47]	CFRP	0.167	4918	1.99	247	Single-skin (full wrapping)
[48–51]	CFRP	0.167	3717	1.61	235	Single-skin (full, partial, and non-uniform wrapping)
[52]	CFRP	0.167	4351	1.85	239	Single-skin and single-skin with additional reinforcement
[16]	CFRP	0.167	3475.9	1.29	270.2	Single-skin multilayered
[53]	CFRP	0.167	4324.2	1.85	233.4	Single-skin multilayered
[56]	CFRP	-	3475.9	1.42	243.5	Single-skin multilayered
[57]	CFRP	0.167	3667.5	1.8	240	Single-skin (full wrapping) and single-skin multilayered
[58]	CFRP	0.167	3667.5	-	240	Single-skin multilayered
[63]	CFRP	0.167	4525	1.71	265	Single-skin (full wrapping and partial wrapping)
[64]	CFRP	0.167	3927	1.62	242	Single-skin (full wrapping)
[65]	CFRP	0.167	3530	1.60	230	Single-skin multilayered

3.2. Stainless Steel

In addition to FRP composites, stainless steel has also been used to confine SWSSC as it also possesses excellent corrosion resistant properties. Furthermore, stainless steel also offers extremely high durability and better fire resistance [81]. Even though the cost of stainless steel is higher than the conventionally used carbon steel tube, the overall life cycle benefits it can provide could be more beneficial. It not only allows the usage of environmentally friendly SWSSC but also reduces the maintenance cost due to its anti-corrosion properties. The stress–strain curve of stainless steel shows a rounded shape without obtaining a yielding plateau, whereas carbon steel shows a linear elastic response

to yield stress followed by a plateau before strain hardening occurs. This results in the behaviour of concrete-filled stainless steel tubes being different from concrete filled carbon steel tubes. For a similar tube thickness, deformation, ductility, and energy dissipation of stainless steel tubes filled with concrete are higher than for a carbon steel tube filled with concrete [26,82,83]. It is also worth noting that the bond performance of stainless steel is poorer than that of carbon steel due to the smooth surface of stainless steel, and suitable measures can improve this condition [81].

To find the tensile properties of stainless steel tubes utilized to provide confinement to SWSSC, coupons are cut from the tubes and tensile coupon tests are usually conducted on them. Few researchers have also conducted compressive strength tests on hollow stainless steel tubes to compare their behaviour with SWSSC--filled tubes under compression. Table 5 summarises the properties of stainless steel tubes used so far along with the confinement scheme for which they are employed. For confined SWSSC, stainless steel tubes have been utilised in all five confinement classifications. However, the vast majority of the research work has studied only single-skin and double-skin confinement schemes. Stainless steel tubes with a square cross section have been used only in double-skin confinement scheme as an inner tube, whereas circular cross sectioned stainless steel tubes have been used in all five of the confinement classifications.

Table 5. Properties of stainless steel tubes used in the literature to confine SWSSC.

References	Shape	Diameter or Side (mm)	Diameter-to-Thickness (or Side) Ratio	$f_{0.2}$ Range (MPa)	f_u Range (MPa)	Confinement Scheme
[24]	Circular	50.9 to 168.4	16.58 to 52.3	225.7 to 281.1	562.1 to 656.4	Single-skin and double-skin (as inner and/or outer tube)
[25]	Circular	47.9 to 168.4	16.99 to 53.4	270.3 to 324.4	575.3 to 647.2	Single-skin and double-skin (as inner and/or outer tube)
[26]	Circular	49.6 to 202.7	16.58 to 101.86	226 to 398.9	562.1 to 732.4	Single-skin and double-skin (as inner and outer tube)
[27]	Circular	47.9 to 102	16.99 to 35.05	225.7 to 324.4	-	Double-skin (as inner tube)
[9]	Circular	49.6 to 168.4	16.58 to 52.3	226 to 398.9	562.1 to 732.4	Double-skin (as inner and/or outer tube)
	Square	50.4 and 50.8	17.82 and 32.73	400.4 and 500.4	686.1 and 688.7	Double-skin (as inner tube)
[33,53]	Circular	219	54.75 and 109.5	294.9 and 304.9	626.3 and 679.6	Single-skin and single-skin multilayered
[38]	Circular	38 to 114	19 to 57	264 to 320.3	676.2 to 752.9	Double-skin (as inner tube)
[39]	Circular	60.5 to 165.2	21.61 to 55.07	288 to 333	686.7 to 742.5	Single-skin
[54]	Circular	76 to 159	15.2 to 53	257.2 to 316.3	657.2 to 793.6	Single-skin and double-tube (inner and outer tube)
[57]	Circular	159	64.9	337.1	665.8	Single-skin and single-skin multilayered
[59]	Circular	219	73	361	674	Single-skin, single-skin with additional reinforcement, and double-tube (as outer tube)

3.3. Carbon Steel

It is well established that carbon steel is bound to corrode when used with SWSSC. Additionally, it is also acknowledged that its ductility is also inferior to that of stainless steel [81]. However, since carbon steel is much more economical than stainless steel, it has attracted reasonable attention for the confinement of SWSSC through some innovative methods. This is usually achieved by avoiding its direct contact with chloride-ion-rich SWSSC. Initially, Zhang et al. [42] wrapped the inner and outer surface of a steel tube with FRP sheets, and the fabricated FRP-steel composite tube was utilised in providing confinement to SWSSC. This was the first study conducted on a single-skin multilayered confinement scheme. It is also worth mentioning that this procedure is challenging to apply

in real-world conditions. It should be noted that while studying single-skin multilayered confinement using carbon steel, researchers have also fabricated carbon steel tubes filled with SWSSC (i.e., single-skin confinement scheme of SWSSC using carbon steel) for comparing the enhancement in mechanical properties after wrapping them with FRP. Nonetheless, single-skin confinement of SWSSC with carbon steel tubes is not recommended as the tube will become corroded.

Carbon steel tubes have also been used in double-tube confinement schemes in some of the studies. In the studies by Su et al. [31] and Wei et al. [35], SWSSC was coupled with conventional concrete, and carbon steel tubes were not in contact with the corrosion causing SWSSC. Double-tube confinement with carbon steel is discussed in detail in Section 4.5 of this paper. Apart from single-skin multilayered and double-tube confinement schemes, carbon steel tubes have not been used in the remaining three confinement schemes. They can also potentially be used in double-skin confinement schemes if coupled with FRP sheets as inner and/or outer tubes. Table 6 summarises geometric and tensile properties of different carbon steel tubes used in the literature to date. So far, carbon steel tubes of only circular cross sections have been explored by researchers. The diameter-to-thickness ratio of these tubes ranged from 19 to 44.5. Furthermore, the average yield strength ranged between 263.8 and 478.3 MPa, and the young's modulus was between 174 and 206 GPa. Diameter-to-thickness ratio of the carbon steel tube is the most essential parameter investigated by the researchers, and it governs the failure mode of the composite column [28,40].

Table 6. Properties of carbon steel tubes used in the literature to confine SWSSC.

References	Shape	Diameter or Side (mm)	Diameter-to-Thickness (or Side) Ratio	f_y (MPa)	E_s (GPa)	Confinement Scheme
[59]	Circular	89	44.50	315	174	Double-tube
	Square	80	40.00	312	176	
[56]	Circular	133	29.56	-	-	Single-skin multilayered
	Circular	159	35.33	-	-	
[55]	Circular	133	33.25	445 ± 15	205 ± 5	Single-skin multilayered
	Circular	133	26.60	445 ± 15	205 ± 5	
	Circular	133	22.17	445 ± 15	205 ± 5	
[40,42]	Circular	133	29.56	328.5	-	Single-skin multilayered
	Circular	133	22.17	306.4	-	
	Circular	133	19.00	311.9	-	
[35]	Circular	159	35.33	317.6	-	Double-tube
	Circular	159	26.50	325.4	-	
[31]	Circular	133	29.56	478.3	205	Single-skin multilayered
[31]	Circular	219	34.76	412.2	-	Double-tube
	Circular	273	34.51	381.8	-	
[28]	Circular	133	29.56	317.6	-	Single-skin multilayered
	Circular	159	35.33	317.6	-	
	Circular	159	26.50	325.4	-	
	Circular	108	27.00	337.4	206.7	
	Circular	133	26.60	264.4	203.6	
	Circular	200	33.33	302.6	201.1	

Note: "-" means that data is not available.

3.4. PVC

Apart from being corrosion-resistant, PVC tubes are also lightweight and inexpensive [84]. However, due to their low strength, the provided confinement effect is lower when compared to carbon steel and FRP tubes. They are also associated with melting when heated [85]. Consequently, PVC as a material for confining SWSSC has been studied little by researchers. However, the confinement capacity of the economically beneficial PVC tubes can be improved if they are used along with other strong confining materials. In a study conducted by Su et al. [31], a carbon steel tube was used as an outer tube alongside an inner PVC tube. Due to the composite action of PVC and steel tube, brittle failure was avoided, and the ductility was also increased. Furthermore, the confinement efficiency of PVC tubes were also improved by wrapping them with CFRP strips. The material properties of the used PVC tubes used in Su et al. [31] are summarised in Table 7.

In a review study conducted on PVC tubes filled with conventional concrete [86], it was concluded that concrete confined with PVC tubes portrays improved load bearing capacity, superior durability, reduced overall weight, and great ductility. Furthermore, the effectiveness of confinement was found to be dependent on the geometry of the PVC tube and strength of the concrete used.

Table 7. Properties of PVC tubes used in [31].

PVC Tube Type	Diameter (mm)	D/t	Hoop Tensile Strength (MPa)
PVC double-wall corrugated tube	110 to 200	22.58 to 29.62	11.1 to 20.04
PVC tube	110 and 160	31.33 and 44.32	19.27 and 33.61

3.5. Aluminium Alloy

Aluminium alloy tubes are also suitable to be used with chloride ions rich SWSSC as they also offer excellent corrosion resistance. Furthermore, they are lightweight, easily malleable, recyclable, and have shiny appearance. However, they have lower load carrying capacity than carbon steel and stainless steel [87,88]. Unlike carbon steel, stress–strain curve of aluminium alloy is defined by a round curve without the presence of a distinct yield point [89]. Figure 3 shows the stress–strain curves of carbon steel, stainless steel, and aluminium [90]. As expected, the confinement efficiency of aluminium alloy tubes also depends on the cross-sectional shape, diameter-to-thickness ratio of the tube and concrete strength [91]. Table 8 summarises the properties of aluminium alloy tubes used so far to confine SWSSC. Only a handful of studies have investigated the usage of aluminium alloy tubes for confinement of SWSSC and they can be classified under single-skin multilayered and double-skin confinement schemes. Even though aluminium alloy is corrosion resistant, it is usually associated with low tensile strength. This makes aluminium not the best choice for confinement when compared with stainless steel and FRP. However, by coupling it with FRP, its inferior tensile properties can be compensated. It should also be mentioned that tubes having only circular cross section have been employed to confine SWSSC.

3.6. High Performance Concrete Based Tubes

In the search for more economical ways to utilise SWSSC in harsher conditions where FRP and stainless steel do not perform well, researchers have explored the usage of high performance concrete based tubes filled with SWSSC. Shan et al. [41] utilised reactive powder concrete (RPC) to make a hollow tube with CFRP hoop and longitudinal bars inside it. RPC is an ultra-high performance concrete made with steel fibres having a compressive strength up to 800 MPa [92]. In addition to high compressive strength, RPC also possess high tensile strength and excellent durability [93,94]. RPC used by Shan et al. [41] had a compressive strength of 153.8 MPa and stainless steel fibres were used in it. When tested under compression, failure mode of RPC hollow tube started with existence of hoop

crack followed by local crushing of tube wall. In a different study, Zhang et al. [60] studied the axial compressive behaviour of premanufactured steel-bar-reinforced engineered cementitious composite (ECC) concrete shells filled with SWSSC. The compressive and tensile strengths of ECC concrete were 71.16 MPa and 10.52 MPa, respectively, and it had polyethylene fibres in it. Both of the aforementioned studies can be classified as single-skin confinement SWSSC with additional reinforcement. However, it should be noted that the reinforcing bars were present in the precast shell or tube rather than infill SWSSC.

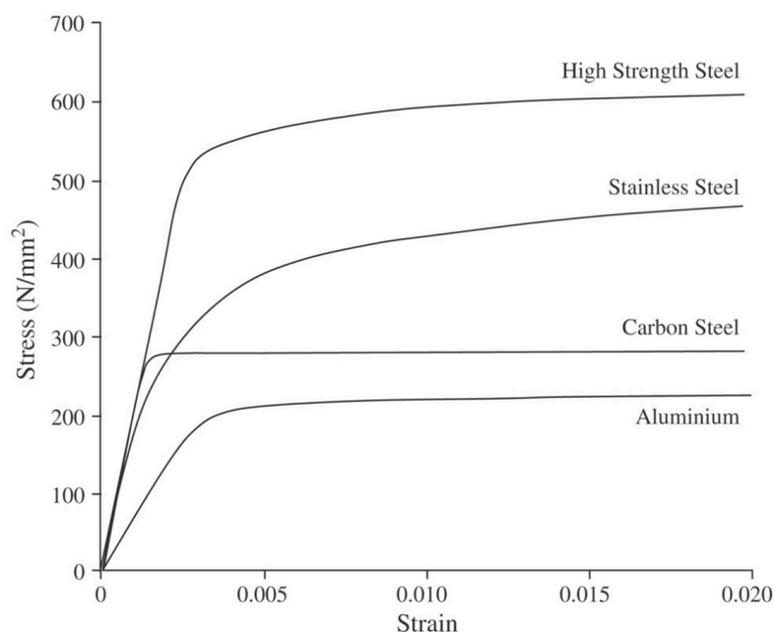


Figure 3. Stress–strain curves of stainless steel, carbon steel, and aluminium [90].

Table 8. Properties of aluminium alloy tubes used in the literature to confine SWSSC.

Reference	Diameter (mm)	Thickness (mm)	Height (mm)	D/t	Average Yield Strength (MPa)	Average Ultimate Strength (MPa)	Elastic Modulus (GPa)	Confinement Scheme Studied
[38]	76	2	300	38	199.8	-	69.2	Double-skin (as inner tube)
[58]	150	3	600	50	190	217.3	69.8	Single-skin multilayered
[65]	130	5 and 10	390	26 and 13	269	295.8	69.8	Single-skin multilayered

4. Confining Schemes

4.1. Single-Skin Confinement

Single-skin confinement of SWSSC can be achieved in three ways. In the first, FRP is used in the form of sheet wrapping to strengthen or confine existing SWSSC columns (Figure 4A). In the second and third, premanufactured FRP tubes and stainless steel tubes, respectively, are utilised and filled with SWSSC (Figure 4B,C).

4.1.1. SWSSC Confined by FRP Wrapping

Fibre-reinforced polymer composites in the form of wraps or jackets have been widely used in the past to enhance the strength and ductility of concrete columns [47]. These FRP jackets are usually installed via a wet layup method with the fibres of the FRP oriented in the hoop direction. When it comes to wrapping of SWSSC with FRP sheets, only concentric axial

compressive loading has been studied so far. Furthermore, different wrapping strategies have been investigated by researchers, and they can be classified into three categories. These are discussed subsequently.

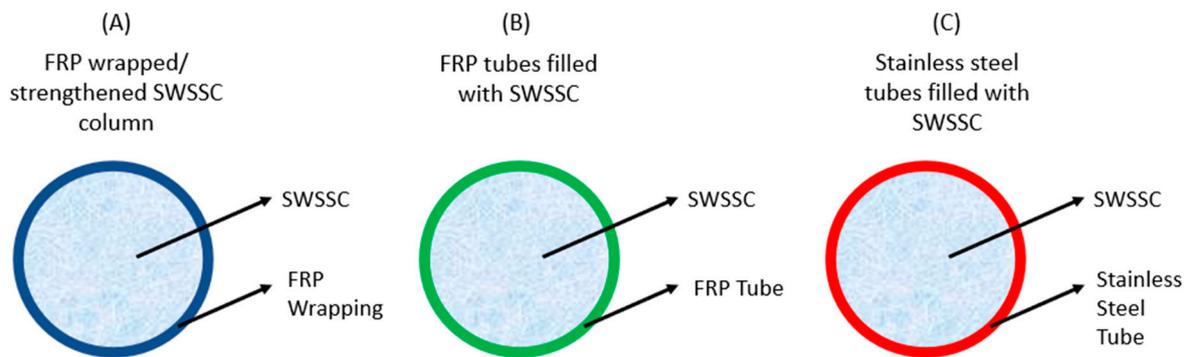


Figure 4. Single-skin confinement of SWSSC.

(A) Fully Wrapped SWSSC Columns

As shown in Figure 5, this type of confinement scheme can be achieved by wrapping the entire height of the SWSSC column with a uniform thickness of FRP. Majority of the existing research on strengthening of SWSSC columns using FRP sheets has been done using fully wrapped confinement scheme. Table 9 summarises the research conducted on fully wrapped SWSSC columns till date. The most influential parameters explored in this confinement scheme are the FRP sheet type, the thickness or number of layers of FRP jackets, and the cross-section of the columns. CFRP, BFRP, and PET-FRP are the three types of FRP sheets that have been used so far to make fully wrapped SWSSC columns. Furthermore, the maximum number of layers of wrapping for all the three types of FRP is three, and the height of the specimens ranged from 300 to 800 mm.

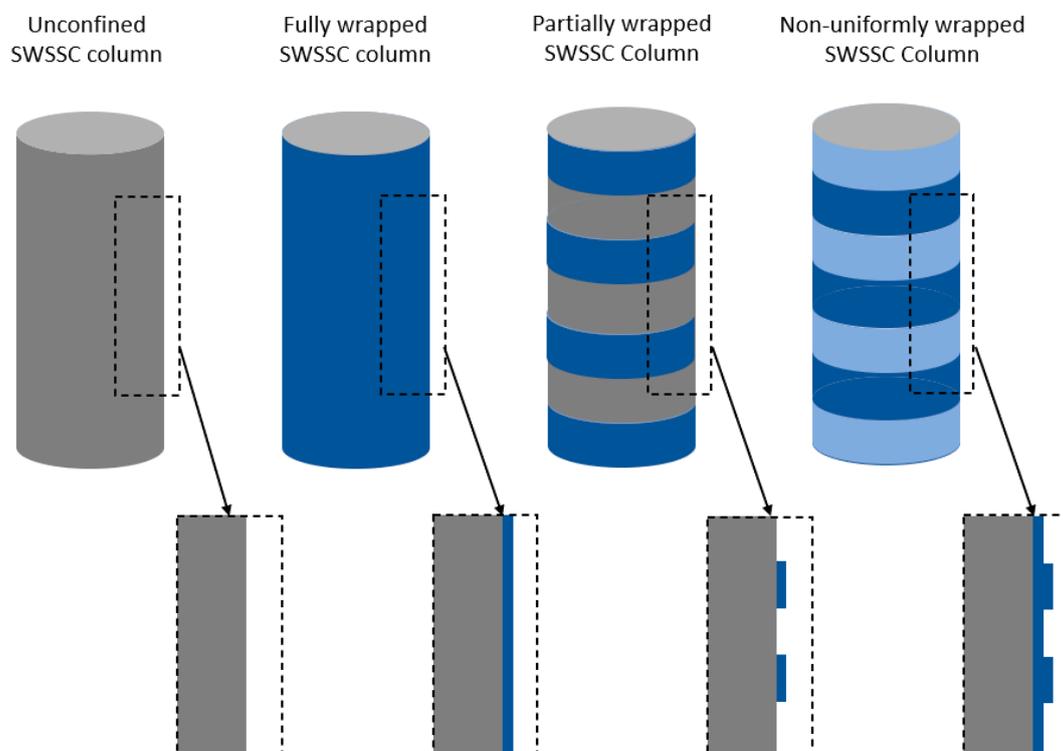


Figure 5. Studied wrapping strategies for SWSSC columns.

Table 9. Research conducted on fully wrapped SWSSC columns.

Reference	Wrapping Material	No of Layers	Cross Section of Specimen	Diameter or Side (mm)	Height (mm)	Increase in 28th Day Compressive Strength after Confinement
[29]	CFRP	1	Square	150	300	19%
	CFRP	2				70%
	CFRP	3				116%
	PET-FRP	1				−10%
	PET-FRP	2				35%
	PET-FRP	3				78%
[36]	BFRP	2	Circular	150	300	8%
	BFRP	3				11%
	CFRP	2				4%
	CFRP	3				7%
[43]	PET-FRP	1	Circular	150	300	27%
	PET-FRP	2				91%
	PET-FRP	3				141%
	CFRP	1				86%
	CFRP	2				112%
	CFRP	3				173%
[47]	CFRP	1	Circular	150	300	46%
	CFRP	2				117%
[48]	CFRP	1	Circular	150	300	75%
	CFRP	2				175%
[49]	CFRP	1	Square	150	300	27%
	CFRP	2				43%
[52]	CFRP	1	Square	200	800	15%
	CFRP	2				23%
[57]	CFRP	1	Circular	159	600	102%
[63]	CFRP	1	Circular	150	300	90%
	CFRP	2				146%
	CFRP	1				51%
	CFRP	2				111%
[64]	CFRP	1	Square	150	300	51%
	CFRP	2				106%
	CFRP	3				154%

The failure of FRP confined SWSSC columns occurs when applied load surpasses ultimate stress of the unconfined SWSSC and it starts to expand in lateral direction, ultimately resulting in the tensile rupture of the FRP [36]. As observed in most of the studies, the failure of CFRP confined circular SWSSC columns takes place because of the sudden rupture of FRP at mid-height, and this is also indicated by a loud noise, whereas for the specimens confined with PET-FRP, the failure comes with limited noise [43]. For fully wrapped SWSSC columns with a square cross sections, irrespective of the type of FRP used and the number of wrapping layers, the failure occurred at one of the edges or corners

of the specimen at the mid-height region [29]. This is because of the existence of more distinct confining pressure at the edges of the specimens where curvature discontinuity exists [49]. Furthermore, with the increasing corner radius, the area of rupture region increases vertically as inner concrete experiences more damage [64].

In general, fully wrapped SWSSC columns display increased compressive strength and deformation capabilities when compared to unconfined SWSSC columns. Given that the stiffness of CFRP is higher than the stiffness of PET-FRP for the same number of wrapping layers, the increase in ultimate load for SWSSC columns wrapped with the former is more than that for SWSSC columns wrapped with the latter. However, the specimens fully wrapped with PET-FRP showed greater axial deformation with significant bulging due to the higher deformation capacity of PET-FRP compared to CFRP [43]. Furthermore, since the ultimate strength of BFRP is lower than CFRP, for a same number of wrapping layers, the increment in ultimate strength of SWSSC columns confined with the BFRP sheets is also lower than the ultimate strength of SWSSC columns confined with CFRP sheets. However, due to the superior deformation capabilities of BFRP sheets, the SWSSC specimens wrapped with them show greater ductility compared to the specimens wrapped with CFRP sheets [36]. As a rule of thumb, irrespective of the type of FRP used, the increase in the ultimate stress and ultimate strain of a fully wrapped SWSSC column is directly proportional to the increase in the number of layers of wrapping.

The stress–strain curve of circular CFRP-wrapped specimens shows a linear elastic portion and a hardening portion. The behaviour of the second branch of the curve is significantly impacted by the FRP properties and the shape of the cross section. The second branch was observed to be linear for circular specimens and nonlinear for square specimens. If the confinement provided by FRP sheets is weak, post-peak softening can also be observed. With the lateral dilation of SWSSC confined by FRP sheets, confining pressure also increases. The dilation rate or the ratio of hoop to axial strain also shows a two-stage curve. The first stage of the curve is linear. The second stage is linear or parabolic for circular or square sections, respectively. Moreover, the hoop strain at any given axial strain decreases with increasing number of layers of FRP sheets [29,43]. For CFRP-confined compression-casted SWSSC, the peak stress was higher and ultimate strain was lower than the normally casted CFRP-confined SWSSC [63]. If recycled aggregates are to be used in FRP sheet confinement, the ultimate strength decreases, and ultimate strain increases with increasing recycled aggregate content. Furthermore, the stress–strain curve shows bilinear response, and with increasing recycled aggregates replacement, the transition stress tends to shift downward [64].

(B) Partially Wrapped SWSSC Columns

From the above section, it is evident that the fully wrapping strategy can significantly enhance the strength and deformation capacity of SWSSC columns. However, when mild strengthening is required, full wrapping can become expensive and inefficient when used in real structures. Because of this reason, few researchers have studied partial wrapping of SWSSC columns. In this confinement scheme, only some portion of SWSSC columns is wrapped through uniform layers of FRP strips along its shaft. This results in the presence of unconfined zones between the two adjacent FRP strips. Yang et al. [48] studied the axial compressive behaviour of circular cross sectioned SWSSC columns partially wrapped with CFRP. Figure 6 shows the details of the studied partial wrapping scheme. Furthermore, the stress–strain relationship and the failure pattern of partially wrapped SWSSC columns are distinct from fully wrapped SWSSC columns [48,49]. So far, only CFRP sheets have been used to study this type of confinement scheme, and the parameters investigated are number of layers of CFRP wrapping, spacing between two adjacent CFRP strips, width of the wrapping strip and the cross section of the column. Table 10 summarises the research done on partial wrapping of SWSSC columns.

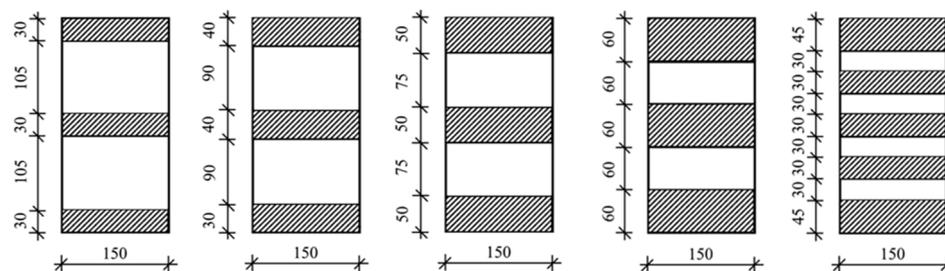


Figure 6. Partial wrapping scheme studied in [48].

Table 10. Research done on partially wrapped SWSSC columns.

Reference	Wrapping Material	Partial Wrapping Details	No of Layers	Cross Section of Specimen	Increase in Compressive Strength after Confinement
[48]	CFRP	3 × 30 mm wide strips (spacing—105 mm)	2 and 4	Circular	12% and 26%
	CFRP	3 × 40 mm wide strips (spacing—90 mm)	2 and 4	Circular	22% and 40%
	CFRP	3 × 50 mm wide strips (spacing—75 mm)	2 and 4	Circular	33% and 63%
	CFRP	3 × 60 mm wide strips (spacing—60 mm)	2 and 4	Circular	52% and 99%
	CFRP	2 × 45 mm strips at the ends and 3 × 30 mm strips in between (spacing—30 mm)	2 and 4	Circular	70% and 133%
[49]	CFRP	3 × 30 mm wide strips (spacing—105 mm)	2 and 4	Square	4% and 10%
	CFRP	3 × 40 mm wide strips (spacing—90 mm)	2 and 4	Square	6% and 20%
	CFRP	3 × 50 mm wide strips (spacing—75 mm)	2 and 4	Square	16% and 23%
	CFRP	3 × 60 mm wide strips (spacing—60 mm)	2 and 4	Square	18% and 22%
	CFRP	2 × 45 mm strips at the ends and 3 × 30 mm strips in between (spacing—30 mm)	2 and 4	Square	24% and 31%
[63]	CFRP	2 × 45 mm strips at the ends and 3 × 30 mm strips in between (spacing—30 mm)	2 and 4	Circular	69% and 150%
	CFRP	2 × 45 mm strips at the ends and 1 × 30 mm strips in between (spacing—90 mm)	2 and 4	Circular	21% and 30%
	CFRP	3 × 52.5 mm wide strips (spacing—75 mm)	2 and 4	Circular	23% and 40%
	CFRP	3 × 60 mm wide strips (spacing—60 mm)	2 and 4	Circular	43% and 72%
[63]	CFRP	2 × 45 mm strips at the ends and 3 × 30 mm strips in between (spacing—30 mm)	2 and 4	Circular	42% and 88%
	CFRP	2 × 45 mm strips at the ends and 1 × 30 mm strips in between (spacing—90 mm)	2 and 4	Circular	23% and 32%
	CFRP	3 × 52.5 mm wide strips (spacing—75 mm)	2 and 4	Circular	20% and 35%
	CFRP	3 × 60 mm wide strips (spacing—60 mm)	2 and 4	Circular	19% and 36%
[52]	CFRP	2 × 100 mm wide strips at the ends and 4 × 45 mm wide strips in between (spacing—105 mm)	2	Square	10%
	CFRP	2 × 100 mm wide strips at the ends and 4 × 60 mm wide strips in between (spacing—90 mm)	2	Square	12%
	CFRP	2 × 100 mm wide strips at the ends and 4 × 75 mm wide strips in between (spacing—75 mm)	2	Square	17%
	CFRP	2 × 100 mm wide strips at the ends and 4 × 90 mm wide strips in between (spacing—60 mm)	2	Square	18%
	CFRP	2 × 100 mm wide strips at the ends and 4 × 105 mm wide strips in between (spacing—45 mm)	2	Square	14%

The failure of partially wrapped circular SWSSC columns starts with the formation of small cracks between the two adjacent strips located near the mid height when the applied stress surpasses the strength of unconfined SWSSC. With increasing load and

increasing deformation of concrete, CFRP strip near mid-height ruptures with a loud noise. As expected, for partially wrapped square sections, the FRP rupture takes place at the corner. For both square and circular cross sectioned SWSSC columns, with the decreasing clear spacing between the adjacent strips, the confining effect created by the CFRP strips increases and the ultimate strength and ultimate strain are improved. It should be noted that the confining effect becomes negligible if the clear spacing between two adjacent strips becomes greater than the diameter or side of the SWSSC column. Additionally, with an increasing number of layers of wrapping for a constant value of clear spacing between two adjacent strips, the confinement effect is intensified, and it is indicated by severe concrete spalling after the failure of CFRP strips. As the microstructure of compression casted SWSSC is denser than normally casted SWSSC, the failure of confined specimens was observed to be more brittle, and the ultimate axial strain was weakened [63].

The occurrence of descending post peak behaviour in the stress–strain curve is more common with increasing clear spacing ratio for partially wrapped SWSSC columns. Unlike fully wrapped sections, a more obvious transition branch is observed which depicts that stress–strain curve has three segments. The lateral strain–axial strain curve of partially wrapped SWSSC columns is characterised by two linear segments and the slope of the curve becomes less steep with a decreasing clear spacing ratio [48,49]. Compression casting has a negative effect on the slope of the second linear segment stress–strain curve compared to normally casted partially confined specimens. As a result, the rate of strength enhancement for compression casted specimens was less than that of normally casted specimens. Furthermore, lateral strain rate of compression casted partially wrapped specimens was higher than normally casted specimens, resulting in lower axial deformation capacity [63].

(C) Nonuniformly Wrapped SWSSC Columns

This type of confinement configuration is a combination of both fully wrapped and partially wrapped confinement schemes, as the SWSSC column is initially fully wrapped with a single layer of FRP followed by partial wrapping with FRP strips on top of the first layer. This results in nonuniform thickness of FRP along the height of the SWSSC column. For the sake of easy understanding, the locations where more than one layer of FRP is present are termed as primary strips region and the locations where only single layer of FRP is present are termed as secondary strips region. The parameters studied so far in this type of confinement scheme are the clear spacing, number of layers of the secondary CFRP strips, and the cross section of the specimen [50,51]. Table 11 summarises the results of the research done on nonuniformly wrapped SWSSC columns.

The failure mode of nonuniformly wrapped SWSSC columns is notably different than fully or partially wrapped SWSSC columns. It starts with the rupture of outer strips of the primary strip region near the mid height denoted by sudden drop in the applied load. Followed by this, the internal FRP layers being relatively intact still have the capacity to carry the axial load. At last, they also rupture with a loud noise. For square specimens, the failure takes place at the corner. Because of the advantages of primary and secondary layers of confinement in nonuniformly confined SWSSC columns, the failure mode is less brittle when compared to fully wrapped SWSSC columns. Moreover, with increasing thickness of the primary strips, the confining pressure can be increased, and it results in a more severe failure of the column. The stress–strain curve of nonuniformly wrapped SWSSC also depicts bilinear shape with a transition segment in between. The slope of the second linear portion became stiffer with decreasing clear spacing ratio of the outer FRP strips. Furthermore, under the same FRP volumetric ratio, the confinement effectiveness of nonuniformly wrapped SWSSC with multiple strips is greater.

Table 11. Research done on non-uniformly wrapped SWSSC columns.

Reference	Wrapping Details (After One Layer of Full Wrapping)	Wrapping Material	No of Layers	Cross Section of Specimen	Increase in Compressive Strength after Confinement
[50]	3 × 30 mm wide strips (spacing—105 mm)	CFRP	2 to 4	Circular	201% to 226%
	3 × 40 mm wide strips (spacing—90 mm)	CFRP	2 to 4	Circular	215% to 247%
	3 × 50 mm wide strips (spacing—75 mm)	CFRP	2 to 4	Circular	221% to 267%
	3 × 60 mm wide strips (spacing—60 mm)	CFRP	2 to 4	Circular	228% to 292%
	2 × 45 mm strips at the ends and 3 × 30 mm strips in between (spacing 30 mm)	CFRP	2 to 4	Circular	256% to 322%
[51]	3 × 30 mm wide strips (spacing—105 mm)	CFRP	2 to 4	Square	133% to 137%
	3 × 40 mm wide strips (spacing—90 mm)	CFRP	2 to 4	Square	141% to 145%
	3 × 50 mm wide strips (spacing—75 mm)	CFRP	2 to 4	Square	144% to 149%
	3 × 60 mm wide strips (spacing—60 mm)	CFRP	2 to 4	Square	144% to 159%
	2 × 45 mm strips at the ends and 3 × 30 mm strips in between (spacing 30 mm)	CFRP	2 to 4	Square	146% to 163%

4.1.2. SWSSC Confined by FRP Tubes

In addition to wrapping with FRP sheets, the strength and stiffness of SWSSC columns have also been found to increase by filling them in premanufactured FRP tubes. An added mechanical advantage of using FRP tubes filled with SWSSC over FRP wrapped SWSSC comes from the ability to sustain a part of the load due to the axial stiffness of the tube itself [95]. In addition to this, the FRP tubes can act as permanent formwork for the column resulting in making construction faster. Many studies have been conducted to study the short-term mechanical properties of SWSSC-filled tubes. It should be noted that long term durability of FRP tubes filled has also gained considerable attention in the past. However, it is beyond the scope of this paper. As summarised in Table 12, the main parameters studied so far when confinement to SWSSC is provided by FRP tubes are the type of FRP tube, diameter (or edge if the cross section is square) of the FRP tube, and its thickness.

CFRP, BFRP, and GFRP are the types of FRP tubes that have been used in the past to confine SWSSC. The majority of the FRP tubes that have been used to confine SWSSC were circular in shape. Only one study exists in which the behaviour of square FRP tubes filled with SWSSC under compression was examined [46]. When FRP tubes are filled with SWSSC, the failure mode changes from the crushing of a hollow tube at the ends to the rupturing of an SWSSC-filled FRP tube along with the crushing of SWSSC. In general, the compressive strength and the ductility of SWSSC can be improved by filling it into premanufactured FRP tubes. This behaviour was observed in all the studies irrespective of the type of FRP tube. Furthermore, the increase in compressive strength of SWSSC filled CFRP tubes is higher than BFRP and GFRP tubes filled with SWSSC because of the stiffer nature of CFRP as compared to GFRP and BFRP [27]. The thickness and diameter of the FRP tubes are also significant in defining the behaviour of SWSSC filled tubes under compression. As a rule

of thumb, with decreasing diameter-to-thickness ratio, the confinement provided increases, resulting in higher compressive strength [30]. It is worth mentioning that there is a lack of understanding on specific effects of fibre orientation and fibre volume fraction of FRP tubes on confined SWSSC. However, it is expected that the increase in compressive strength will be greater if fibre volume fraction is increased and the angle of non-longitudinal fibres increases with respect to axial direction [96]. More investigation in this area is needed to confirm this. The failure of the SWSSC-filled FRP tube initiates when the applied load surpasses the capacity of the unconfined SWSSC. If the applied load is increased beyond this point, the specimen gradually fails with the rupture of the FRP tube, indicated by a loud noise [9].

Table 12. Research conducted on FRP tubes confined by single-skin SWSSC columns.

Reference	Tube Type	Manufacturing Process	Cross Section	Length (mm)	Parameters Studied
[24]	GFRP and BFRP	FW	Circular	150 and 400	FRP type, diameter-to-thickness ratio
[25]	GFRP	FW	Circular	400	Diameter-to-thickness ratio
[27]	CFRP, BFRP and GFRP	FW	Circular	150 and 400	FRP type, diameter-to-thickness ratio and exposure to salt water
[9]	BFRP	FW	Circular	300 and 400	Diameter-to-thickness ratio
[30]	BFRP	In situ spirally wrapped	Circular	300	Thickness of tube
[32]	BFRP	In situ spirally wrapped	Circular	450	Thickness of tube and load eccentricity
[37]	GFRP	FW	Circular	300, 450 and 600	Diameter-to-thickness ratio, axial loading (monotonic and cyclic) and temperature
[44]	GFRP	FW	Circular	800	Diameter-to-thickness ratio, concrete type (OAC and SWSSCAC)
[45]	GFRP	FW	Circular	300 and 600	Thickness of tube, type of aggregates and inclusion of BFRP needles
[46]	CFRP, BFRP and GFRP	FW	Square	150	FRP type, side length and thickness of FRP sections
[61]	GFRP	FW	Circular	400	Tube thickness and amount of structural polypropylene fibre
[62]	GFRP	FW	Circular	400	Tube thickness and presence of epoxy coated longitudinal bars

4.1.3. Single-Skin Confinement of SWSSC by Stainless Steel Tubes

Carbon steel has been widely used in the past to enhance the capacity of ordinary or conventional concrete due to the confinement effect provided by it. In addition to this, the infill concrete also helps in delaying the buckling of the carbon steel tube. However, carbon steel cannot be used to directly confine SWSSC as the chloride ions present in the seawater and sea sand will result in the corrosion of carbon steel. Therefore, stainless steel tubes are usually used, as they possess excellent corrosion resistant properties. The stress–strain behaviour of stainless steel is different from carbon steel which makes the response of concrete filled stainless steel tubes different than concrete filled carbon steel tubes [82].

Thickness of the tube, diameter of the tube, and strength of infill SWSSC are the parameters that have been explored by researchers when it comes to stainless steel tubes confined SWSSC. Table 13 summarises the research conducted so far on SWSSC filled

stainless steel tubes. It should be mentioned that stainless steel tubes having a cross section other than circular have not been investigated so far. Under axial compression, usually before the arrival of peak point, no visible damage or buckling of stainless steel tube is observed. With a further increase in axial load, failure takes place with local outward buckling of the tube. If length-to-diameter ratio is higher, failure occurs due to local and global buckling of the stainless steel tube [24,25]. The ultimate capacity is considered as the first peak. If no peak was observed, 5% axial strain was taken as the peak load by Li et al. [26], whereas 2% axial strain was taken as peak load by Cai and Kwan [39]. After the peak load is attained, the stainless steel tubes can still sustain the load [24,26]. For some of the specimens, the rapid drop in load was observed to be followed by a pickup stage [59], whereas strain hardening was observed for specimens that were highly confined. When the diameter of the tube is kept constant, the platform of the load strain curve changes from horizontal to continuously rising as the thickness is increased. Figure 7 shows the axial load versus axial strain curve of specimens from Li et al. [26] and Cai and Kwan [39].

Table 13. Summary of studies performed on SWSSC filled stainless steel tube.

Reference	Cross Section	Length (mm)	Diameter-to-Thickness Ratio	Parameters Studied
[24]	Circular	150 and 400	16.6 to 52.3	Diameter-to-thickness ratio
[25]	Circular	400	17.2 to 52.1	Diameter-to-thickness ratio
[26]	Circular	150 to 600	32.4 to 101.9	Diameter-to-thickness ratio and slenderness ratio
[33]	Circular	500	54.75 and 109.5	Loading scheme (cyclic and monotonic)
[39]	Circular	151 to 412	21.6 to 55.1	Concrete strength and diameter-to-thickness ratio
[53]	Circular	500	54.75 and 109.5	Thickness of tube and strength of concrete
[59]	Circular	600	73	-

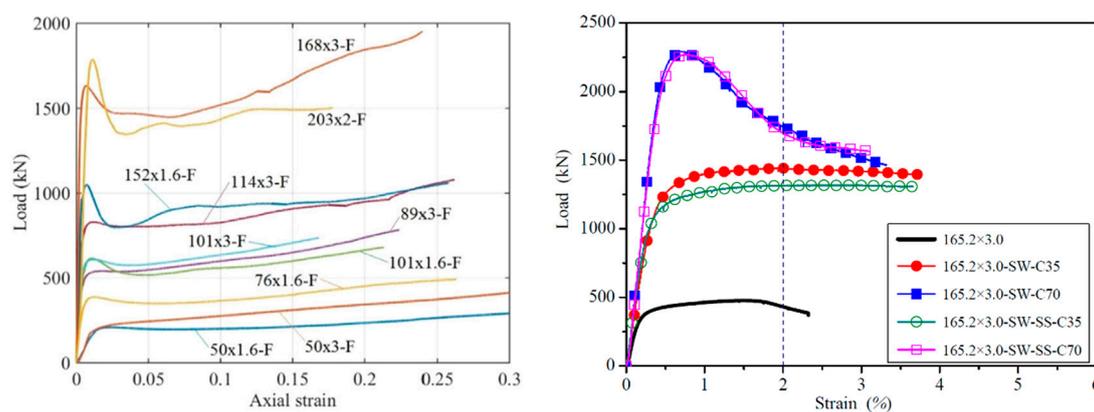


Figure 7. Axial load strain curves for SWSSC confined by stainless steel tubes ((left) [26] and (right) [39]).

The most crucial parameter which governs the behaviour of SWSSC-filled stainless steel tube is the diameter-to-thickness ratio of the stainless-steel tube. As seen in Table 13, a wide extent of diameter-to-thickness ratio ranging from 16.6 to 109.5 has been explored by researchers so far. In general, with increasing diameter-to-thickness ratio, the level of confinement decreases. Moreover, confinement caused by stainless steel tubes is slightly lower than FRP tubes, but it lasts for a larger axial strain [25]. It was also observed that even after reaching the peak load, unlike SWSSC confined by FRP, fractures in the confinement

providing stainless steel are not observed as it has outstanding deformation abilities. Furthermore, SWSSC-filled stainless steel tubes show greater ductility than SWSSC confined by FRP. In addition to monotonic axial loading, the behaviour of cyclic axial compression on stainless steel tube confined SWSSC has also been explored by Zeng et al. [33]. Elephant foot buckling was observed at both ends, which shows that bonding between the stainless steel tube and SWSSC was not good and that cyclic loading can further weaken the bond between the tube and SWSSC.

4.2. Single-Skin Multilayered Confinement of SWSSC

When it comes to seawater sea sand concrete filled tubes, stainless steel tubes and FRP tubes have been the preferred choice due to the offered electrochemical corrosion resistance. However, stainless steel tubes are less economical, and FRP tubes lose load bearing capacity after their brittle failure. With these constraints in mind, researchers have recently utilised cheaper carbon steel along with FRP sheets to confine SWSSC in a very innovative way. For instance, Zhang et al. [42] wrapped FRP sheets on the inner and outer surfaces of a steel tube to curate FRP carbon steel composite tube and filled it with SWSSC. By using this composite FRP carbon steel tube, the problem of deterioration of carbon steel can be avoided as it does not come in direct contact with the chloride ions from SWSSC and cost-effective construction can be promoted. This type of composite single-skin confinement scheme, in which more than one type of material is used to provide confinement, can be referred to as single-skin multilayered confinement scheme. To achieve this type of confinement scheme with FRP sheets, epoxy-resin-soaked FRP sheet is first attached to the outer surface of the tube. To paste the sheet on the inner surface of the tube, a cylindrical object with epoxy resin impregnated FRP sheet is then rolled inside the same tube [28,34]. Apart from FRP sheets, filament-wound GFRP tubes have also been paired with carbon steel tubes in one of the studies by sandwiching the carbon steel tubes between two GFRP tubes [55].

As the carbon steel tube enters the yielding stage, confinement mechanism of the outer FRP sheet is activated, and it restrains the buckling of the tube. At the ultimate load, fracture of FRP sheets occurs and this is marked by a significant load drop. Residual bearing capacity is then observed for the specimens. In general, the ultimate bearing and deformation capacity are enhanced by increasing the number of FRP layers and reducing the diameter-to-thickness ratio of carbon steel tube. Furthermore, with increasing diameter-to-thickness ratio of carbon steel tube, the failure mode of the specimens has the tendency to shift from shear failure to extrusion expansion failure due to the increase in lateral constraint of tube [28,40]. Additionally, as expected, SWSSC filled carbon steel tubes wrapped with CFRP sheets provided higher load carrying capacity and SWSSC filled carbon steel tubes wrapped with BFRP sheets provide higher deformation capacity [28,40]. The stress–strain curve of FRP confined carbon steel filled SWSSC is composed of four stages: elastic stage, nonlinear transition stage, hardening or strengthening stage, and post peak or residual stage. Stress increases linearly with increasing strain in the elastic stage, and the confining effect of steel and FRP is not active yet. The yielding of steel tubes is represented by the nonlinear transition stage. The confinement provided by FRP results in the secondary hardening stage. After the ultimate load at failure of FRP, a large drop occurs, and residual stage is seen due to the confinement provided by steel [28,40,55]. Moreover, the effects of type and thickness of FRP on the stress–strain behaviour are more substantial than the thickness of carbon steel tube [40,42,55]. Figure 8 shows the axial stress–strain curves of single-skin multilayered confined specimens from Zhang et al. [42] and Sun et al. [55]. Under axial cyclic loading, similar stress–strain behaviour is observed and the brittleness of FRP failure is slowed down. Furthermore, higher unloading stiffness is observed, but it decreases with increase in number of cycles [34].

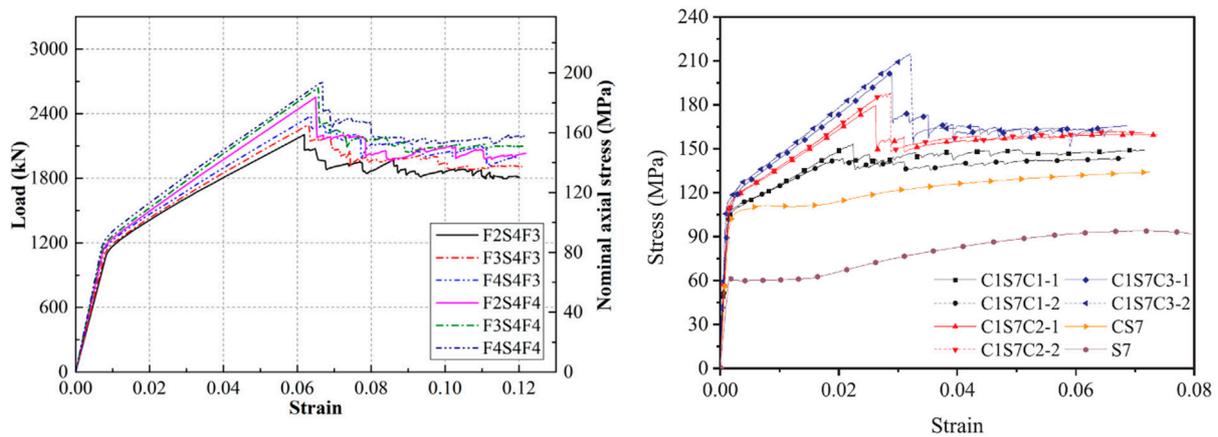


Figure 8. Axial load strain curves for single-skin multilayered confined SWSSC with FRP and carbon steel ((right) [42] and (left) [55]).

To restrain the outward buckling of stainless steel tubes filled with SWSSC, they can also be paired with FRP wrapping, and this further increases the load-bearing capacity. Huang et al. [16] studied the axial compressive performance of SWSSC filled stainless steel tubes wrapped with CFRP sheets and observed that increasing thickness of stainless steel tube and increasing number of layers of FRP wrapping enhance the ultimate bearing capacity of the composite columns. The failure mode is governed by the fracturing of FRP wrapping and local buckling of stainless steel tubes. Owing to the high ductility of stainless steel, a high residual load bearing capacity is still present after the failure [16,53]. The stress–strain curve of an FRP-wrapped stainless-steel-filled SWSSC column is also similar to that of FRP-confined carbon-steel-filled SWSSC columns with four stages [16,57]. Under cyclic compression, the axial load–axial strain curves of monotonic compression were observed to be enveloped under the curve of cyclic response [33]. In a different study, another innovative approach was adapted to strengthen SWSSC columns using stainless steel wire mesh sandwiched between two layers of FRP sheets [36]. It was observed that stainless steel wire mesh prevented the loss of bearing capacity of specimens after the sudden fracture of FRP sheets (CFRP and BFRP) while increasing the ultimate stress and ultimate strain. However, the integrity of the composite tube made up of stainless steel mesh and FRP sheets should be ensured as they do not reach their respective ultimate strengths at a same time.

In addition to carbon steel and stainless steel tubes, aluminium alloy tube has also been paired with FRP sheets in few of the studies to form a single-skin multilayered confinement scheme [58,65]. The behaviour of the load–strain curve was similar to single-skin multilayered specimens with carbon steel and stainless steel wrapped with FRP. Table 14 summarises the research conducted on single-skin multilayered confinement to date. The major parameters studied in this confinement scheme are diameter-to-thickness ratio of the tubes, type of FRP sheets, number of layers of FRP sheets on the inner and outer surfaces of the carbon/stainless steel tubes, and SWSSC strength. The effect of presence of FRP sheet on the inner surface of aluminium alloy tube as a parameter was investigated by [57,58]. It was observed that the failure mode of core concrete was crushing when inner FRP was not present and shear failure when inner FRP was present.

4.3. Single-Skin Confinement of SWSSC with Longitudinal Reinforcement

Unlike the homogenous or isotropic carbon steel and stainless steel tubes, FRP tubes are anisotropic in nature [97]. Because of this reason, they hold the ability to provide tensile strength in either axial or hoop direction. However, it is reasonable to assume that structural columns in real situations undergo through bending moment creating eccentric and lateral loads also. As a result, internal reinforcement is required to avert SWSSC crack propagation and improve the deformation capacity. Consequently, some researchers

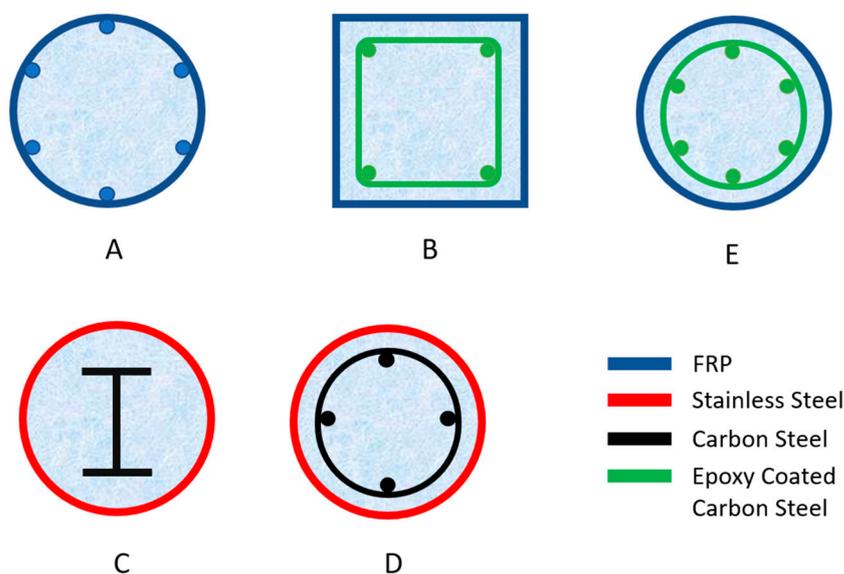
have studied FRP tubes confined SWSSC columns with longitudinal reinforcements. For obvious reasons, the reinforcing bars having anticorrosion properties (FRP rebars and epoxy coated steel rebars) have been the choice so far due to the presence of chloride in SWSSC [98]. Table 15 summarises the research work done on single-skin confined SWSSC columns with additional reinforcement and Figure 9 shows the cross sections of the investigated specimens.

Table 14. Summary of research on single-skin multilayered confined SWSSC columns.

Reference	Confinement Through	Concrete	Tests Performed	Parameters Studied
[28]	FRP sheet wrapping on inner and outer surface of carbon steel tube	Seawater sea sand coral aggregate concrete	Axial compression	Diameter-to-thickness ratio of steel tube, type of FRP, and number of layers of FRP on the outer surface of steel tube
[33]	FRP sheet wrapping on outer surface of stainless steel tube	Seawater sea sand concrete	Monotonic and cyclic axial compression	Three cyclic loading patterns, thickness of stainless steel tube, and number of layers of CFRP jacket
[34]	FRP sheet wrapping on inner and outer surface of carbon steel tube	Seawater sea sand concrete	Cyclic axial compression	Number of layers and type of FRP
[36]	Stainless steel wire mesh sandwiched between two separate FRP sheet layers	Seawater sea sand concrete	Axial compression	Number of layers of steel wire mesh, FRP type, and number of layers of FRP sheets
[40]	FRP sheet wrapping on inner and outer surface of carbon steel tube	High strength seawater sea sand concrete	Axial compression	Diameter-to-thickness ratio of steel tube, type of FRP, and number of layers of FRP on the outer surface of steel tube
[42]	FRP sheet wrapping on inner and outer surface of carbon steel tube	Seawater sea sand concrete	Axial compression	Diameter-to-thickness ratio of steel tube, type of FRP, and number of layers of FRP on the outer surface of steel tube
[16]	FRP sheet wrapping on outer surface of stainless steel tube	Seawater sea sand concrete	Axial compression	Diameter of stainless steel tubes, thickness of stainless steel tubes, and number of layers of CFRP sheets
[53]	FRP sheet wrapping on outer surface of stainless steel tube	High and normal strength seawater sea sand concrete	Axial compression	Strength of SWSSC, thickness of stainless steel tube, and number of layers of CFRP sheets
[58]	FRP sheet wrapping on inner and outer surface of aluminium alloy tube	Seawater sea sand concrete	Axial compression	CFRP sheets pasting position (inner and outer surface of tube) and number of layers of CFRP
[55]	Carbon steel tube sandwiched between two filament-wound GFRP tubes	Seawater sea sand coral aggregate concrete	Axial compression	Thickness of steel tube and thickness of inner and outer GFRP tube
[56]	FRP sheet wrapping on inner and outer surface of carbon steel tube	Seawater sea sand coral aggregate concrete	Axial compression	Diameter-to-thickness ratio of steel tube and number of layers of CFRP on the outer surface of steel tube
[57]	FRP sheet wrapping on inner and/or outer surface of stainless steel tube	Seawater sea sand concrete	Axial compression	Location and number of layers of FRP sheets
[65]	FRP sheet wrapping on the external surface of aluminium alloy tube	Seawater sea sand recycled aggregates concrete	Axial compression	Number of layers of FRP sheets, thickness of the aluminium tube, and the strength of the concrete

Table 15. Summary of research on single-skin confined SWSSC columns with additional reinforcements.

Reference	Concrete	Outer Confinement	Reinforcement Details	Loading	Parameters Studied
[30]	SWSSCAC	BFRP tube (in situ)	8 mm diameter longitudinal BFRP bars	Axial compression	Thickness of BFRP tube and presence of BFRP bars
[32]	SWSSCAC	BFRP tube (in situ)	8 mm diameter longitudinal BFRP bars	Eccentric compression	Thickness of BFRP tube, presence of BFRP bars and eccentricity
[52]	SWSSC	Fully wrapped with CFRP sheets Uniform partial wrapping with CFRP sheets	12 mm and 8 mm diameter epoxy coated steel bars as longitudinal and transverse reinforcement, respectively	Axial compression	Thickness of CFRP wrapping, internal reinforcement ratios, spacing between CFRP strips
[59]	SWSSC	Stainless steel tube Stainless steel tube	Carbon steel I section in the middle of cross section 12, 16, or 20 mm diameter longitudinal bars and 8 mm diameter spiral stirrups made with carbon steel	Axial compression	- Spacing of the spiral reinforcement and diameter of the longitudinal reinforcement
[62]	SWSSCAC	Filament wound GFRP tube	12 or 16 mm diameter longitudinal bars and 10 mm diameter circumferential stirrups made with epoxy coated steel	Axial compression	Thickness of GFRP tube and reinforcement ratios

**Figure 9.** Single-skin confinement with longitudinal reinforcement ((A) [30,32], (B) [52], (C) and (D) [59], (E) [62]).

Lu et al. [30] studied the effect of BFRP bars as longitudinal reinforcement on SWSSCAC-filled in-situ-made BFRP tubes under axial compression. The BFRP bars were pre-bonded, while the BFRP tubes were made with BFRP sheets. The test parameters were the thickness of BFRP tubes and the presence of BFRP bars. It was observed that the increment in bearing capacity and reduction in peak compression strain of specimens with BFRP bars were up to 24.6% and 12.7%, respectively. In a different study, similar BFRP tubes with pre-bonded BFRP bars filled with SWSSCAC were tested under eccentric compression and witnessed

that for a given eccentricity, ultimate load and displacement increased with increasing BFRP tube thickness and reinforcement ratio [32]. To support the longitudinal reinforcement bars in confined SWSSC columns, Ying et al. [62] studied the effect of circumferential stirrups made of epoxy-coated steel with varying longitudinal and circumferential reinforcement ratios. It was concluded that with increasing reinforcement ratios, the deformation and load-bearing capacities of the specimens were increased. Furthermore, when it comes to partially wrapped SWSSC columns with internal longitudinal and transverse reinforcement, the confinement is better when the FRP sheets and transverse reinforcement are not placed at the same height [52].

4.4. Double-Skin Confinement of SWSSC

Double-skin confinement scheme refers to SWSSC sandwiched between inner and outer confinement layers. This results in the column being hollow at the centre, and hence, its self-weight can be reduced. This becomes beneficial for long columns as the bending stiffness is also enhanced due to the presence of more materials away from the neutral axis of the column [99]. Furthermore, a double-skin confinement also delivers the possibility to use more than one type of material to provide confinement to the infill concrete which allows the composite column to take advantage of distinct properties of two different materials and make the column more customisable in terms of its structural behaviour.

So far, majority of the studies conducted on double-skin-confined SWSSC have utilised premanufactured tubes. Only one research group has used FRP sheets as an outer confinement layer [38]. Table 16 summarises the types of outer and inner tubes and the parameters investigated in various studies so far. Different types of FRP (CFRP, GFRP, and BFRP) and stainless steel tubes have been explored in this confinement scheme as all of them are suitable to use due to their corrosion resistant properties. Apart from the diameter and thickness of the utilised inner and outer tubes, the volume of the inner void (represented as void ratio) also plays an important role in defining the structural behaviour of these columns [25]. For a double-skin column under compression with stainless steel as outer tube and FRP as inner tube, the buckling of inner tube results in sudden drops in load. However, if FRP is used as an outer tube and stainless steel as inner tube, FRP tube ruptures earlier than the large deformation of inner stainless steel tube resulting in the resistance of inner expansion of SWSSC by the inner stainless steel tube. However, if both the tubes are made of FRP, the failure happens due to the buckling of the inner FRP tube [24,25]. On the other hand, if both the tubes are made of stainless steel, the column exhibits a more ductile failure. Furthermore, with increasing void ratio, the failure is represented by a greater number of folds in the tubes [26]. If used as an outer tube, FRP results in more strength enhancement and stainless steel provides greater deformation. As expected, in all the FRP types, CFRP provides highest confinement due to its higher hoop strength.

4.5. Double-Tube Confinement of SWSSC

Concrete filled double-tube-confined columns are composed of two concentric tubes and concrete is filled inside them such that there is no hollow space. When it comes to double-tube-confined seawater sea sand concrete, a variety of materials such as stainless steel, carbon steel, FRP and PVC have been used as inner and outer tubes to provide confinement. A combination of stainless steel tubes and filament wound FRP tubes (BFRP and CFRP) were used as inner and outer tubes to form double-tube SWSSC columns by Li and Zhao [9]. In a similar way, Huang et al. [54] studied double-skin SWSSC columns with stainless steel as outer tube and CFRP or stainless steel tubes as inner tubes. It was observed that after the yielding of the outer stainless steel tube, the load-bearing capacities of specimens with inner CFRP tubes decrease with its fracture. On the contrary, specimens with stainless steel as inner tubes witnessed greater residual load-bearing capacity. Chen et al. [59] proposed a different double-tube-confined SWSSC column with stainless steel as outer tubes and carbon steel as inner tubes. This was done to reduce the consumption of stainless steel and the corrosion of carbon steel was weakened by the

impenetrable environment formed by steel tubes that limit the access to water and oxygen. The inner carbon steel made the plunging section of the load displacement curve less steep.

Table 16. Summary of research on double-skin confined SWSSC columns.

Reference	Outer Confinement	Inner Confinement	Parameters Studied
[24]	Stainless steel (Circular)	Stainless steel (Circular)	Outer and inner tube type, outer and inner tube diameter-to-thickness ratio
	Stainless steel (Circular)	CFRP (Circular)	
	CFRP (Circular)	Stainless steel (Circular)	
	CFRP (Circular)	CFRP (Circular)	
	Stainless steel (Circular)	BFRP (Circular)	
	BFRP (Circular)	Stainless steel (Circular)	
	BFRP (Circular)	BFRP (Circular)	
[25]	Stainless steel (Circular)	Stainless steel (Circular)	Outer and inner tube type, outer and inner tube diameter-to-thickness ratio
	Stainless steel (Circular)	GFRP (Circular)	
	GFRP (Circular)	Stainless steel (Circular)	
[26]	Stainless steel (Circular)	Stainless steel (Circular)	
[9]	Stainless steel (Circular)	BFRP (Circular)	Void ratio and tube slenderness ratio
	Stainless steel (Circular)	BFRP (Square)	
[38]	FRP wrap (Square)	Stainless steel (Circular)	Tube type and void ratio
	FRP wrap (Square)	Aluminium tube (Circular)	

The concept of double-tube confinement of SWSSC was further extended by pairing it with conventional or normal concrete made with river sand and fresh water. To do this, normal concrete was filled between the hollow space between the inner and outer tubes and SWSSC was filled inside the inner tube. It is worth mentioning that this type of twin concrete setup gives an opportunity to use steel bars as reinforcement in double-tube columns. Wei et al. [35] studied a double-tube specimen with a steel tube as the outer tube and an in-situ-fabricated CFRP tube as the inner tube. The space between the inner tube was filled with SWSSC, and the space between inner and outer tube was filled with normal concrete. Su et al. [31] studied a similar double-tube configuration with an inner tube made of PVC tubes. In addition to the thickness of steel and FRP tubes, the ratio of SWSSC and normal concrete at the cross section of the double-tube specimens also plays important role in governing the strength increase index as the two concretes might have different strength. The details of the cross sections of the specimens and the studied parameters are summarised in Table 17.

Table 17. Summary of research on double-tube-confined SWSSC columns.

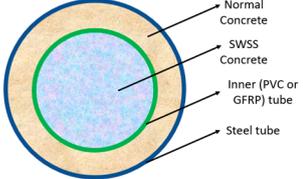
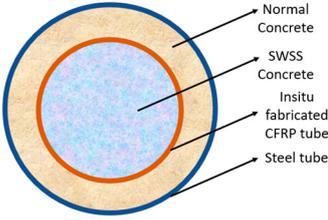
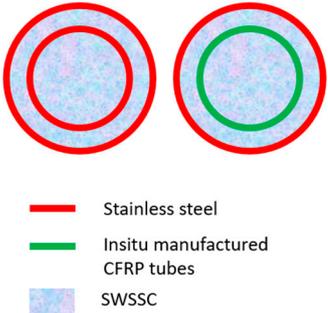
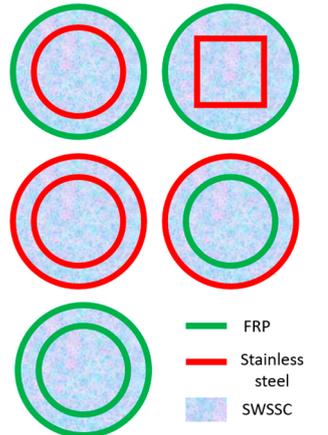
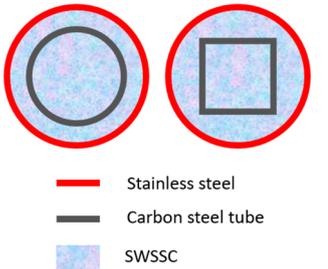
Reference	Specimen Cross Section	Preparation of Specimen	Parameters Studied
[31]		Initially, SWSSC filled PVC or FRP tubes were fabricated. They were then placed inside the steel tubes and the remaining hollow space between the prefabricated SWSSC filled PVC or FRP tubes and steel tube was filled with normal concrete.	Types and thickness inner tube (PVC and GFRP), strength of concrete, wrapping area of CFRP strips

Table 17. Cont.

Reference	Specimen Cross Section	Preparation of Specimen	Parameters Studied
[35]		FRP sheets impregnated with epoxy resin were circumferentially wrapped around an acrylic tube. After the curing of the adhesive, the acrylic tube was separated, and the FRP tube was fabricated. The fabricated FRP tube was then placed inside the steel tube using a wooden bottom template. Followed by this, SWSSC was poured inside the FRP tube and normal concrete was poured inside the hollow space between the fabricated FRP tube and the steel tube.	Diameter of the in situ fabricated FRP tube, number of layers of FRP and thickness of steel tube
[54]		For double-tube specimens made with stainless steel tubes (inner and outer), after placing both the tubes concentrically, SWSSC was poured inside the hollow spaces. For double-tube specimens made with CFRP tube (inner) and stainless steel tubes (outer), CFRP core tubes were in situ fabricated using CFRP sheets. After placing the core FRP tube inside the outer stainless steel tube using a bottom plate, SWSSC was poured into the hollow spaces.	Outer stainless steel tube thickness, type of inner core tube (CFRP and stainless steel), diameter and thickness of inner core tubes
[9]		Double-tube specimens had combinations of stainless steel, filament-wound CFRP, and BFRP tubes constructed by placing the inner tube inside the outer tube and filling the empty space with SWSSC.	Type of outer tube (BFRP and stainless steel), type of inner tube (BFRP, CFRP and stainless steel), shape of inner stainless steel tube (circular and square), diameter and thickness of inner and outer BFRP and stainless steel tubes
[59]		The specimens were made by installing the square and circular carbon steel tubes inside the outer stainless steel circular sections. The hollow spaces were then filled with SWSSC.	Shape of inner carbon steel tube (square and circular)

5. Discussion and Recommendations for Future Research

This review was conducted to address the requirement of a systematic classification system and consideration of a wide variety of confinement providing materials on the available literature of confined SWSSC columns. A direct comparison of different confining schemes is not feasible as they have their own use cases based on the design requirements of the structure. However, a comparison between the most commonly used materials to confine SWSSC can be done. When it comes to economic feasibility, the upfront cost of steel is significantly lower than that of stainless steel or FRP. Moreover, the maintenance

and repair cost of steel is much higher than that of stainless steel or FRP due to the lack of inherent corrosion resistance. Furthermore, transportation and installation of FRP is more economical than steel and stainless steel due to its light weight. With environmental perspective in mind, it can be said that the production of steel and stainless steel is a highly energy-intensive process and results in significant gas emissions, whereas the production of FRP requires less energy and generates less emissions. When it comes to the material properties, FRP shows the best corrosion resistance and great tensile properties. However, they also have low elastic moduli, low ductility, and poor temperature resistance. On the other hand, both steel and stainless steel have greater ductility and fire resistance. With these in mind, combined usage of FRP with steel or stainless steel is recommended to achieve cost efficiency and excellent structural performance.

For coastal and offshore infrastructure, greater corrosion resistance is not the only desirable attribute. For instance, structures such as wharfs, docks, and sea bridges are prone to severe damage from accidental vessel collisions. Offshore structures, such as wind farms, oil rigs, and drilling platforms, are susceptible to excessive vibrations from the heavy machinery. Consequently, high ductility and high energy absorption are also necessary for these types of structures. These characteristics become more significant if these structures are located near seismic fault lines. It is imperative to focus on these topics in order to encourage the implementation of confined SWSSC for marine infrastructure.

The following conclusions and future recommendations can be established.

5.1. Concluding Notes

- Due to the presence of corrosion-inducing chloride ions, materials with anti-corrosive properties have been the choice of researchers when it comes to the confinement of SWSSC. So far, FRP in the form of sheets and tubes has been the most used, followed by stainless steel tubes. Furthermore, CFRP is widely preferred over other types of FRP because of its exceptional stiffness.
- In addition to FRP and stainless steel, other materials such as aluminium alloy tubes, PVC tubes, and high-performance concrete tubes have also been used in a few studies. Despite the poor corrosion resistance offered by carbon steel tubes, they have also been innovatively used to confine SWSSC by avoiding their direct contact with SWSSC. This technique has the potential to bring down the cost involved in making confined SWSSC columns.
- Mechanical properties of SWSSC can be effectively enhanced by confining it through the above-mentioned materials, as the composite action from confinement generates superior structural performance. With the employed confinement materials, a total of five different confining schemes have been explored so far, and all of them have their own distinct behaviours under compressive loading.
- For any given confinement scheme, the efficiency of confinement predominantly depends on the material and geometrical properties of the confinement providing materials (such as type and thickness of FRP sheets, fibre orientation and the type of FRP tubes, diameter-to-thickness ratio and cross-sectional shape of the FRP tubes and/or stainless steel tubes, and type of additional reinforcement) and the material properties of SWSSC itself.
- In addition to fully wrapped confinement, partial wrapping and nonuniform wrapping of SWSSC columns have proven to be efficient when only mild strengthening is needed. This has the potential to make strengthening of existing SWSSC columns more economical.
- Distinct stress–strain behaviour is observed for different confinement schemes. For instance, single-skin confined SWSSC columns usually depict a linear elastic region and a hardening region, provided adequate confinement is present. Whereas single-skin multilayered confined SWSSC columns usually have a four-stage stress–strain curve.
- Apart from the conventional natural coarse aggregates, coral aggregates and recycled aggregates have also been used to make confined SWSSC. However, their inclusion

deteriorates the mechanical properties of SWSSC, and they behave differently under confinement.

5.2. Future Recommendations

- Majority of the studies on confined SWSSC have used control compressive strength ranging from 30 to 50 MPa. More efforts could be put into studying the behaviour of high performance SWSSC under different confinement schemes with various confinement providing materials. This is needed as high strength concrete is brittle in nature and its ductility can be potentially increased through confinement.
- Most of the research conducted in this area has focused solely on axial concentric monotonic load. More studies are required on different loading conditions such as eccentric compression and cyclic compression to better understand the behaviour of confined SWSSC columns under real life conditions.
- Experimental results obtained could be extensively used to do more parametric studies through finite element modelling.
- To promote the usage of confined SWSSC where high deformation and energy absorption are needed, partial replacement of aggregates with recycled rubber aggregates can be studied. This will be beneficial for marine infrastructures with similar structural requirements. Inclusion of rubber in concrete is associated with enhanced ductility and energy absorption. However, it also results significant reduction in compressive strength due to the soft nature of rubber and its poor bond with cement matrix. Confinement can be a potential solution to restore the loss in mechanical properties.
- Waste materials such as recycled glass, recycled plastic, antimony tailings, and recycled ceramic as replacement for aggregates in SWSSC could be studied under confinement. However, it is known that the inclusion of such materials usually comes with decreased workability, reduced compressive strength and poor bond at ITZ. Confinement not only has the potential to diminish this inferior performance, but it will also support the ideology of reduction in the dependency on virgin materials and make SWSSC more sustainable.

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