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Behaviour of Concrete Filled Steel Tube (CFST) Subjected to Shear: A Review

Mohammad Awad

M.Sc. Student, Civil Engineering Department, Faculty of Engineering,
The Hashemite University, Zarqa, Jordan

ABSTRACT

Concrete-filled steel tubes represent common structural members for modern civil engineering projects such as high-rise buildings under shear and axial loads. Because of excellent composite functional characteristics, the axial load-carrying capacity of concrete increases due to ductility and confinement provided by the steel tube. Shear behavior is one of the most important CFSTs that ensures the integrity of members and the whole structure. The paper first provides a database including CFST shear experiments and then exploits this database to present a global review of the shear behavior of CFSTs. The paper tries to analyze the available literature on the shear behavior of CFSTs. Special attention will be paid to the circular and rectangular hollow types of CFST, which, in view of their importance, have not been given enough attention in information sources. This study examines some of the critical parameters affecting the ultimate shear strength of CFST members-such as material properties, geometrical configurations, and composite action between steel tube and concrete fill. The presented research also adds to the understanding of CFST shear performance, besides providing design expressions related to the contribution of individual steel and concrete. These research outcomes contribute to the development of safe and efficient applications of CFST in structural engineering.

KEYWORDS: *Concrete-filled steel tubes (CFST), shear behaviour, structural engineering, rectangular CFSTs, composite action, shear strength, experimental studies.*

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INTRODUCTION

Behaviors of Concrete-Filled Steel Tubes are one of the important research areas in structural engineering, due to the fact that CFSTs find wider applications in contemporary civil engineering. CFST members are composite construction consisting of a steel tube filled with concrete in which the properties of both are combined to yield improved performance for various loading conditions. The steel tube confines the concrete core, thus increasing its compressive strength and ductility, and the concrete prevents local buckling of the steel tube and contributes to stiffness and general strength of the member. In fact, all these properties have made CFSTs find extensive applications in high-rise buildings, bridges, and seismic-resistant structures where high strength, ductility, and energy dissipation are required. Whereas the axial and flexural behavior of CFSTs has been widely studied and is reasonably well understood, the shear behavior of such members has been relatively neglected despite its importance in practical applications. In structural members subjected to lateral loads caused by earthquakes, wind, and vehicular impacts, shear forces are usually dominant. Understanding the shear behavior of CFST members is critical for their safe and effective application in critical structural applications such as bridge piers and columns located in seismic regions. Besides, the shear performance of CFSTs is also closely related to their failure mode, energy dissipation capacity, and overall structural stability.

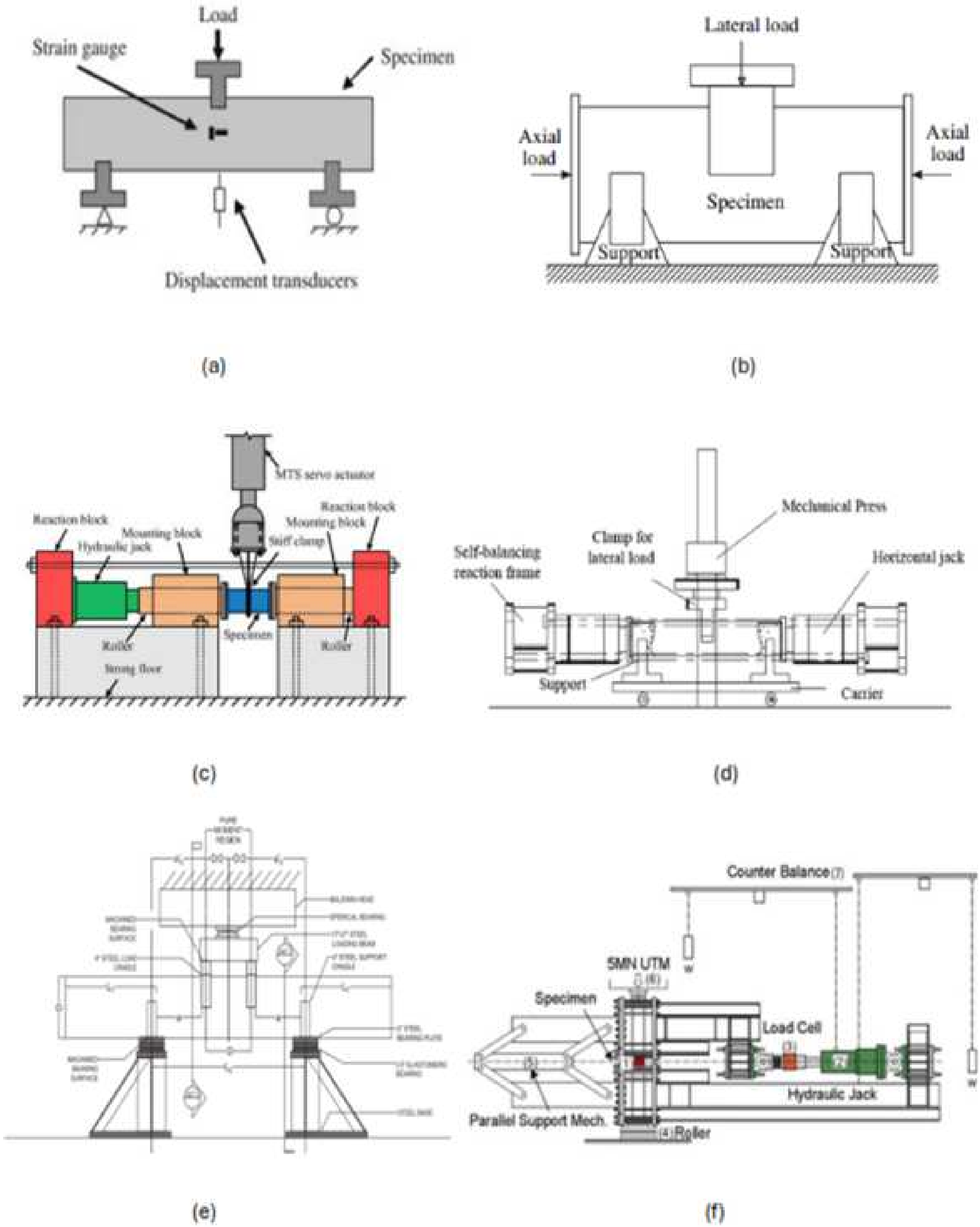

Figure 1 Schematic of test setup used in experimental tests: (a) Xu et al., (b) Qian et al, (c) Ye et al, (d) Xiao et al, (e) Lehman et al, (f) Nakahara and Tokuda

the shear performance of CFSTs is also closely related to their failure mode, energy dissipation capacity, and overall structural stability. Researchers into the shear performance of CFSTs have also been able to determine that influencing parameters include those material properties: concrete compressive strength and yield strength of the steel; and geometrical factors: cross-sectional shape, circular or rectangular, and thickness of the steel tube. The interaction between the steel tube and concrete core plays a very important role in the determination of the CFST shear resistance. Despite these developments, there is still a major gap in knowledge regarding CFST shear behavior: for example, the mechanisms behind the shear forces transferred between the steel tube and the concrete core are not at all clear yet. Most the research done so far has revolved around only circular sections of CFST members, leaving another very common configuration-rectangular CFST members-out in the cold. Since the complex composite behavior of CFSTs under shear loading cannot be fully represented by the existing design codes and equations, predictions for the ultimate shear strength of CFSTs are usually made with inaccuracy. This paper reviews the shear behavior of CFSTs and determines the mechanism and parameters that affect their behavior. This review is supported by experimental studies.

Experimental Data

A literature review of experimental and analytical studies of Concrete-Filled Steel Tubes (CFSTs) was conducted to better understand the shear behaviour of CFSTs. The studies included various CFSTs with circular and rectangular cross-sections to test their behaviour under lateral and cyclic shear loading. The data collected provides a good basis to study the parameters affecting their shear behaviour.

Some studies focused on the shear behaviour of circular CFSTs which are more common in engineering practice. For example, Xiao, C., et al.(Xiao, Cai et al. 2012) conducted shear tests on 50 circular CFSTs to investigate their behaviour under lateral shear loading and to determine their ultimate shear strength. Xu, C., et al. (Xiao, Cai et al. 2012) studied the shear resistance of 35 circular CFSTs, the interaction between the steel tube and the concrete core under shear forces. Qian, J., et al.(Qian, Cui et al. 2007)contributed to this area by testing 29 circular CFSTs, the effect of geometric and material properties on their shear capacity.

More experimental studies on circular CFSTs were conducted by Nakahara, H. and R. Tsumura (Nakahara and Tsumura 2014) who studied the shear behaviour of short circular CFST columns. They investigated the failure mechanisms and shear transfer mechanisms within these members. Nakahara and Tokuda (Tokuda 2012) studied the shear behaviour of short circular CFST columns and identified the critical parameters affecting their ultimate shear strength. Bruneau, et al.(Bruneau, Kenarangi et al. 2018) also studied CFSTs including two circular CFSTs to understand their structural behaviour under shear loading. Lehman, D., et al. (Lehman, Roeder et al. 2018) conducted experimental tests to study the shear behaviour of circular CFSTs and provided detailed experimental data. To complement their experimental work, Lehman, D., et al. (Lehman, Roeder et al. 2019) later conducted analytical studies to compare their models with experimental results and validated the predictions for CFST shear behaviour and the interaction between the steel and concrete components. Besides studies on circular CFSTs, some researchers extended their studies to include both circular and rectangular CFSTs to compare the effect of cross-sectional shape on shear behaviour. Ye, Y., et al.(Ye, Han et al. 2016) conducted extensive shear tests to investigate the behaviour of CFSTs with both circular and rectangular cross-sections under lateral shear loading. Their study showed the difference in performance between these two shapes and provided valuable information on the role of shape in shear resistance. Koester, B. D.(Koester 2000) provided experimental data on rectangular CFSTs and studied their ultimate shear strength and failure modes. SAKINO, K. and H. ISHIBASHI (Koester 2000) contributed to this area by investigating the behaviour of CFSTs under cyclic shearing forces combined with constant axial forces and studied the effect of combined loading on both circular and rectangular cross-sections. CFSTs have been tested under various loading conditions through experimental programs using different test setups. The test programs used three-point loading, reversed curvature loading, double curvature loading with or without axial force. The schematic of the test setups used in these experimental studies are shown in Figure 1(a)-(f) each to address specific aspects of CFST behaviour under shear and combined loading. experimental program shown in Figure 1(a) and Figure 1(b) was three-point loading without axial force to isolate the lateral shear loading on CFST specimens. This configuration was used by Xuet al.(Xiao, Cai et al. 2012) and Qian et al.(Qian, Cui et al. 2007) who used displacement transducers and strain gauges to measure deformation and internal stress distribution. The experiments showed how geometric properties such as diameter-to-thickness ratio (D/t) and length-to-diameter ratio (a/D) affect the ultimate shear capacity of CFST members. The experimental program in Figure 1(c) was double curvature loading which simulates shear forces in multi-span members subjected to bending at two critical locations. This configuration was used by Ye et al.(Ye, Han et al. 2016) who tested specimens with circular and square cross-sections. The setup used hydraulic jacks and reaction blocks to induce double curvature, to study the combined effect of geometric shape, material properties and axial force on the shear behaviour of CFSTs. The results showed the different failure modes of circular and square cross-sections and the role of shear yield and deformation in multi-span configurations. The test setup in Figure 1(d) was three point loading with axial force as conducted by Xiao et al.(Xiao, Cai et al. 2012). This configuration simulated the combined effect of shear and axial force on CFST members which are common in real world applications such as columns in high-rise buildings or bridge piers. The use of axial force in the tests allowed the researchers to study the interaction between axial compression and lateral shear forces, and the effect of axial force ratio (P/Po) on the ultimate shear strength and failure mechanisms of CFSTs. The experimental program in Figure 1(e) was four-point loading to study the shear behaviour of CFST specimens. This test setup used by Lehman et al.(Lehman, Roeder et al. 2018) was chosen because it is cost effective compared to double curvature setup. Additionally, the four point loading method clearly separated the zones of shear yielding and deformation from the zones of flexural yielding, providing a sharper focus on shear behaviour. The program gave important insights on the mechanics of shear force distribution and the contribution of steel and concrete to overall shear resistance. The experimental program in Figure 1(f) was reversed curvature loading with axial force as conducted by Nakahara and Tokuda (Tokuda 2012). This setup simulates the condition where the structural members are bending in opposite direction with axial compression. The test used parallel support mechanism and hydraulic jacks to induce reversed curvature. This program gives us the combined effect of reversed bending and axial force, so we can see the behaviour of CFST under earthquake loading.

Table 1 Specimen specifications and experimental results for CFST Circular

Researchers	Specimen#	D (mm)	t(mm)	a/D	D/t	Fy (MPa)	f'c (MPa)	P/P_0	Vu (kN)
Yong Ye (Ye, Han et al. 2016)	20	10	2-5	0.05-0.15	40-60	325-450	30-60	0-1	150-400
Xiao et al. (Xiao, Cai et al. 2012)	50	160-170	3-6	0.1-0.5	25-60	370-150	25-35	0-0.75	400-1100
Lehman et al. (Lehman, Roeder et al. 2018)	22	508	6.35	0.1-1	50-80	330-530	35-90	0 -0.1	1900-4300
Nakahara and Tokuda (Tokuda 2012)	5	166.12	45-5	0.5	33-34	530-545	45-65	0-0.5	340-920
Xu, C., et al. (Xu, Haixiao et al. 2009)	35	140-170	2.9-3.7	0.1-1	35-60	360-375	30-40	0	250-500
Bruneau et al. (Bruneau, Kenarangi et al. 2018)	2	30-50	0.6	0.35-0.45	50-70	350-400	20-35	0	1750-2000
Qian et al. (Qian, Cui et al. 2007)	29	194	5.5-7.5	0.1-0.5	35-36	330-430	40-70	0-0.8	900-2200
Nakahara and Tsumura (Nakahara and Tsumura 2014)	14	160-170	2-5	0.5	30-75	460-550	45-70	0 - 0.5	420-730

Table 1 and 2 shows various CFST geometries and loading conditions to emphasize the importance of understanding how material properties, geometric characteristics and experimental configurations affect shear behaviour. Circular CFSTs are the most studied due to their confinement properties and structural performance but the inclusion of rectangular CFSTs by researchers such as Ye, Y., et al.(Ye, Han et al. 2016), Koester, B. D(Koester 2000)., and SAKINO, K. and H. ISHIBASHI (SAKINO and ISHIBASHI 1985) gives us more information on less studied configurations. The studies together highlight the key parameters that govern the shear resistance of CFSTs, material properties (concrete compressive strength and steel yield strength), geometric (cross-sectional shape and steel tube thickness) and loading conditions (lateral shear, cyclic loading and combined axial-shear forces).

Table 2 Specimen specifications and experimental results for CFST Rectangular.

Researchers	Specimen#	B (mm)	t (mm)	(a/B)	B/t	Fy (MPa)	f'c (MPa)	P/P_0	Vu (kN)
Yong Ye (Ye, Han et al. 2016)	18	120	2	0.07-0.15	60	335-420	30-60	0-0.5	150-500
Koester (Koester 2000)	9	200-305	6-12	0.75	20-32	360-375	40-55	0	1030-2720
SAKINO, K. and H. ISHIBASHI (SAKINO and ISHIBASHI 1985)	21	95-105	2.2-4.3	1-1.5	24-45	285-320	15-26	0-0.5	75-190

In this study, the shear strength equation provided in the American Institute of Steel Construction (AISC)(Construction 2022) code to was used as a normalization tool to standardize and compare experimental shear force data from various research papers. This equation accounts for the combined contribution of the steel tube and the concrete infill to the shear resistance of concrete-filled steel tubes (CFSTs).

$$V_n = 0.6\, F_y A_v + 0.06 K_c A_c \sqrt{f'_c}$$

Where:

A_v= shear area of the steel portion of a composite member. The shear area for a round section is equal to 2As/π, and for a rectangular section is equal to the sum of the area of webs in the direction of in-plane shear.

Ac = area of concrete infill,

Kc = 1 for members with shear span-to-depth, greater than or equal to 0.7

= 10 for members with rectangular compact composite cross sections and shear span-to-depth less than 0.5

= 9 for members with round compact composite cross sections and shear span-to-depth less than 0.5

= 1 for members having other than compact composite cross sections, for all values shear span-to-depth.

The term $0.6\, F_y A_v$ represents the steel tube's contribution to shear resistance, determined by its yield strength and Shear area of steel. Similarly, $0.06 K_c A_c \sqrt{f'_c}$ quantifies the concrete's contribution, based on its compressive strength and the area of the concrete. The coefficients 0.6 and 0.06 are reduction factors that account for material performance under shear conditions.

Using this as a normalization basis served multiple purposes. First, it allowed for a common comparison of experimental results across different studies, each of which may have tested specimens with different dimensions, material properties and geometric ratios. By normalizing the experimental shear force against the theoretical strength (Vn), the variability in the experimental setup was minimised and we could directly evaluate the experimental-to-theoretical shear strength ratio (Vexp/Vn). This normalization allowed us to see how various parameters – shear span to depth ratio, axial load levels and geometric configurations – affect the shear behaviour of CFSTs. Ratios close to one meant the theoretical prediction matched the experimental result, while significant deviations meant there were factors not captured by the AISC equation. These could be localized concrete cracking, wall deformation in the steel tube or non-uniform stress distribution. Using this normalization highlighted the differences between the theoretical models and real-world behaviour and provided a basis to assess the accuracy and reliability of the AISC code's shear strength equation for CFSTs. By analysing these normalized results, we found trends that could guide future updates to the code and improve its prediction. This normalization was crucial to have a common framework to interpret the experimental data and to advance the understanding of CFST shear behaviour under different loading and boundary conditions.

Effect of axial ratio

Figure 2 shows the relationship between the axial ratio and shear strength for the CFST specimens. Green points are for circular specimens and purple points are for rectangular specimens. The data for circular CFST specimens shows a clear trend where the shear strength increases with the axial ratio. This is because the circular steel tube provides more confinement to the concrete core to perform better under combined axial and shear loading. The uniform confinement in circular specimens reduces stress concentrations and delays the failure, thus more contribution to the overall shear resistance.

As the axial ratio increases, the green points show less scatter, meaning the circular CFSTs become more predictable under higher axial loads. This shows that circular sections are better in mobilizing shear strength under combined loading. On the other hand, the data for rectangular CFST specimens shows a weaker correlation between axial ratio and shear strength. The shear strength of rectangular specimens is generally lower than circular specimens across the range of axial ratios. This is because rectangular steel tubes provide less confinement to the concrete core, resulting to uneven stress distribution and higher likelihood of local buckling or cracking of the concrete core. Also, rectangular specimens show more scatter in shear strength, especially at lower axial ratios. This is because rectangular sections are more sensitive to geometric imperfections, material properties and boundary conditions. Even at higher axial ratios, the increase in shear strength for rectangular specimens is not as significant as for circular specimens.

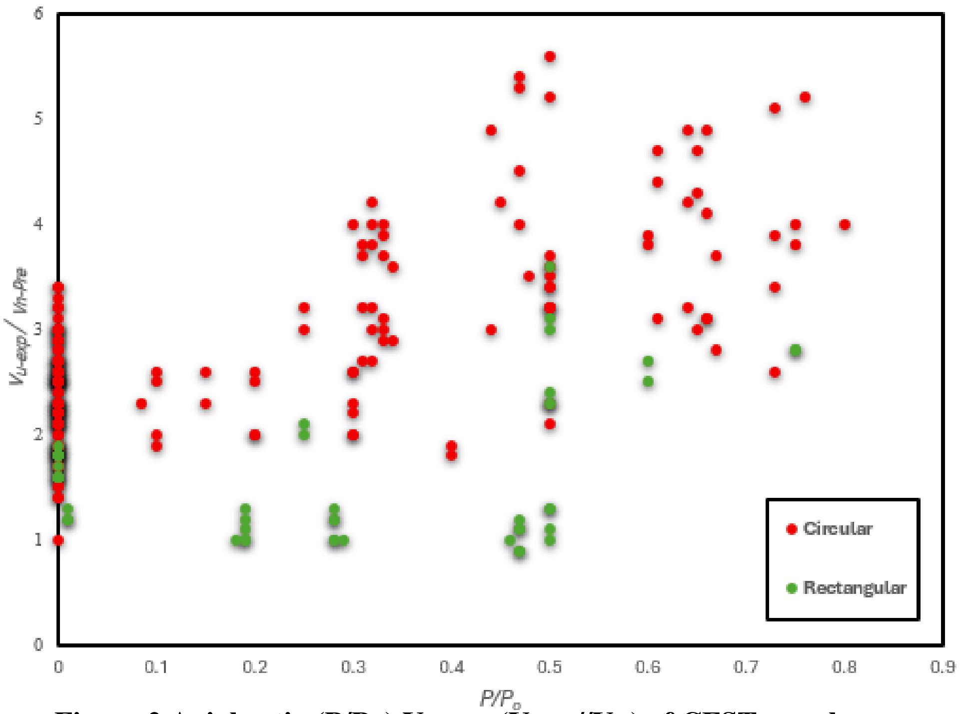

Figure 2 Axial ratio (P/Po) Versus (Vexp//Vn) of CFST members.

Figure 2 shows the advantage of circular CFSTs in resisting shear under axial loading. The confinement provided by circular sections allows better utilization of both steel and concrete, resulting to higher and more consistent shear strength. Rectangular CFSTs are functional but have lower shear resistance and more variability, hence more careful design consideration is needed when using non-circular sections. Figure 3 shows the effect of axial ratio (P/Po) on normalized shear strength (Vexp/Vn) while accounting for the shear span-to-depth ratio (a/D). Across all (a/D) groups, the shear strength decreases as the axial ratio increases. This is expected behaviour for CFST specimens under combined axial and shear loading. Specimens with lower a/Da/D ratios have the highest normalized shear strength. These points are concentrated on the upper part of the graph, especially at low to moderate axial ratios. This means that specimens with small shear spans (relative to their depth) resist shear better, likely due to arching action and reduced bending. Specimens with moderate a/Da/D ratios have slightly lower shear strength than the green points. The distribution of these points shows a transition in behaviour where the shear response is less dominated by arching and more by flexural mechanisms. Specimens with high (a/D) ratios have the lowest normalized shear strength. These points are concentrated on the bottom part of the graph, especially at high axial ratios. This is due to flexural behaviour and reduced shear resistance as the shear span increases.

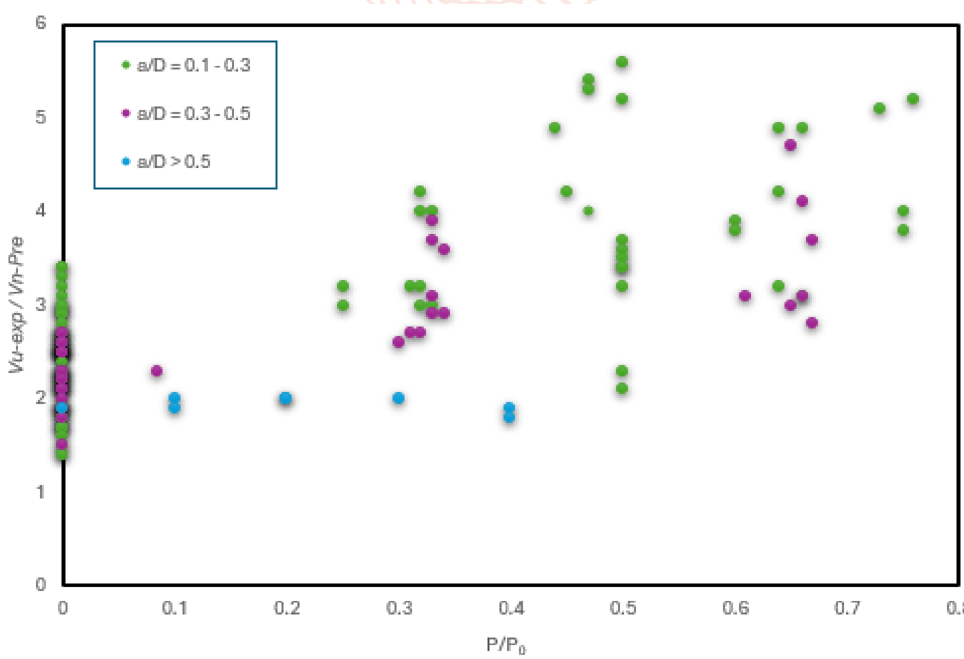

Figure 3 Axial ratio (P/Po) Versus (Vexp//Vn) considering the effect of the shear span-to-depth ratio.

Effect of Shear to Span Ratio

Fig 3 and Fig 4 show the interplay between geometric and loading parameters that affect the shear strength of concrete filled steel tubes (CFST). Fig 3 shows the relationship between the axial ratio and the normalized shear strength with the shear span to depth ratio. The data shows that lower (a/D) ratios (green points) give higher normalized shear strength as the specimens benefit from more arching action. Specimens with higher shear span to depth ratios show a big reduction in shear strength as they transition from shear dominated to flexure dominated behaviour. This shows the combined effect of axial load and shear span on CFST.

Fig 4 shows the effect of shear span to depth ratio (a/D) on circular and rectangular CFST specimens. The green points are for circular cross-sections and the purple points are for rectangular cross-sections. The data confirms the findings in Fig 3, showing a big reduction in normalized shear strength as (a/D) increases. But Fig 4 adds another dimension by showing the effect of cross-sectional geometry. Circular specimens give higher shear strength than rectangular ones, especially at lower (a/D) values. This is because the circular steel tube provides more confinement to the concrete core and allows it to resist shear better. Rectangular specimens are more sensitive to increasing (a/D) with a bigger reduction in shear strength. This means the weaker confinement and stress concentration in rectangular specimens makes them unable to maintain shear resistance as (a/D) increases. By comparing Fig 3 and Fig 4, it can be seen that while axial ratio (P/Po) and shear span to depth ratio (a/D) both affect CFST behaviour, the cross-sectional geometry adds another layer of complexity. Circular CFST specimens are more robust in shear over a wider range of (a/D) values, so they are a better choice for applications where shear performance is critical.

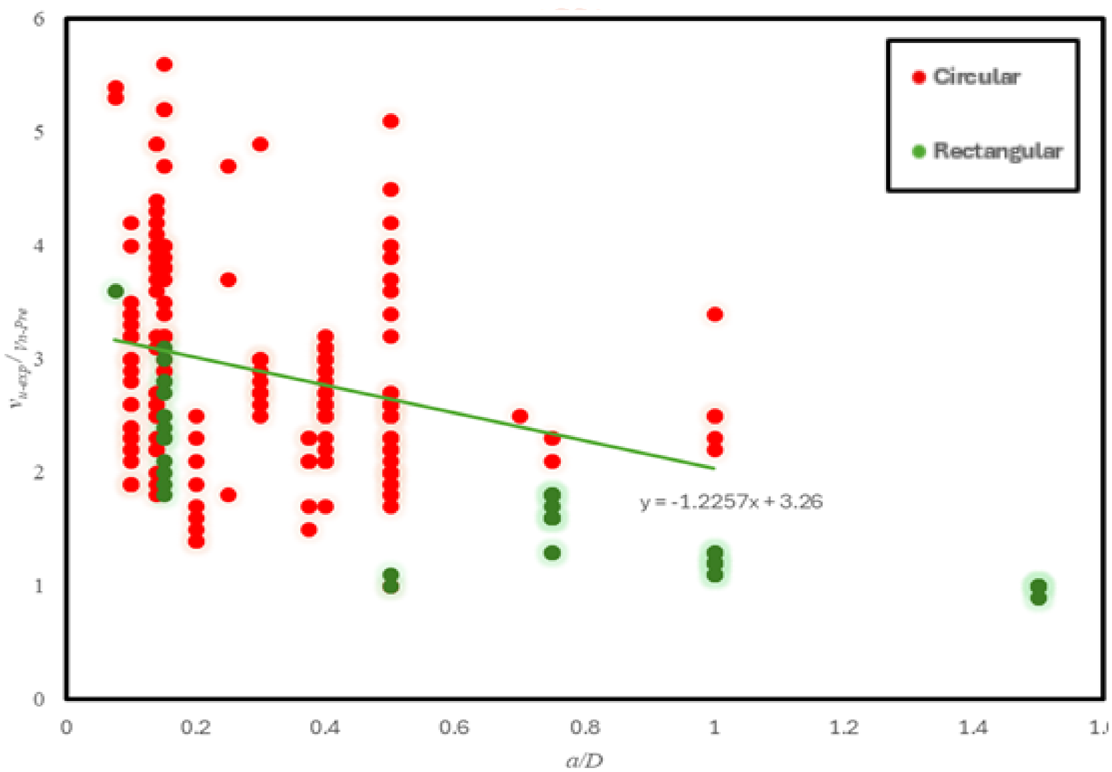

Figure 4 Shear span to Depth Ratio (a/D) Versus (Vexp//Vn) of CFST members.

Shape Effect

The behaviour of Concrete-Filled Steel Tubes (CFSTs) is affected by many factors. Among these factors, the cross-sectional shape plays a major role in the structural performance of CFSTs under shear loading. To isolate and understand the effect of shape, Ye, Y., et al. did an experimental study to compare circular and square concrete-filled steel Tubes specimens. Some of the results are shown in Figure 5 and we will use those to see how the cross-sectional shape affects the shear strength while all other variables are kept constant. The specimen design ensured that the material properties and dimensions were the same for both circular and square samples. The key parameters such as the yield strength of the steel tube, the compressive strength of the concrete core and the dimension of the specimens were controlled. The diameter of the circular specimens was made equal to the width of the square specimens so that the cross-sectional area was the same for both shapes. This eliminated the confounding variables and allowed a direct and fair comparison of the two cross-sectional shapes under the same condition.

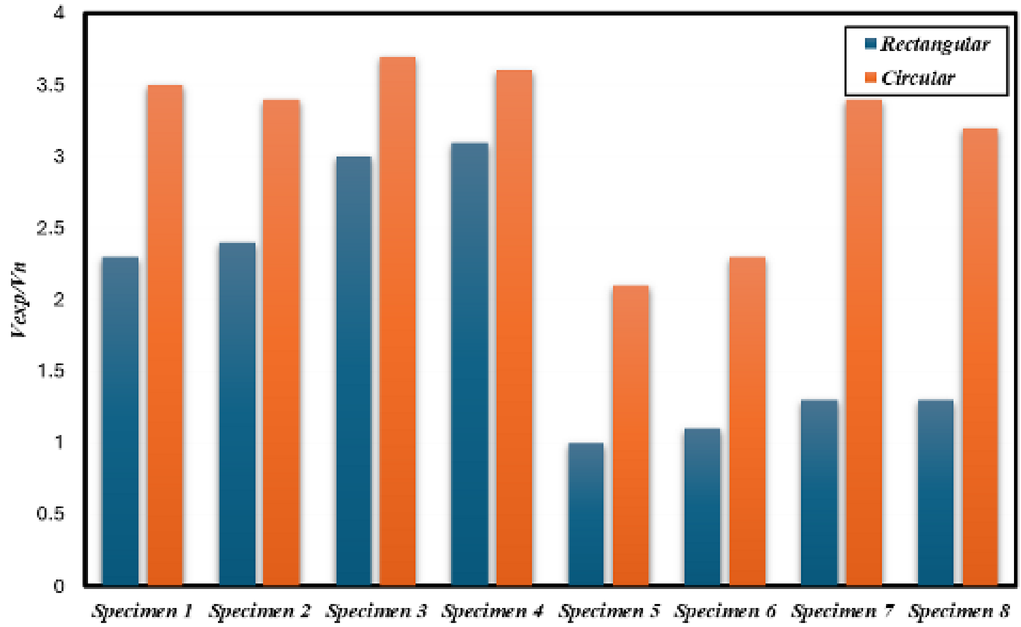

Figure 5 Comparisons of (Vexp/Vn) between Rectangular and Circular CFST Members.

the experimental results presented in Figure 5 shows clearly that circular CFSTs outperform in terms of shear strength. The data shows that circular specimens always outperform square specimens, and the difference becomes more pronounced as the shear strength increases. This indicates that confinement plays a major role in the structural behaviour of CFSTs under shear loading. In circular sections, the steel tube provides a more uniform confinement to the concrete core which resists shear forces more effectively and delays the failure. In square sections, the confinement mechanism is less effective due to the presence of sharp corners where the stress concentrates. These stress concentrations reduce the steel-concrete interaction and limit the shear capacity of square CFSTs.

Effect of another Parameter

The shear behaviour of Concrete-Filled Steel Tubes (CFST) is affected by several parameters that plays a big role in their overall performance under shear loads. One parameter that may affect the shear strength is the diameter-to-thickness ratio (D/t) as shown in Figure 6.

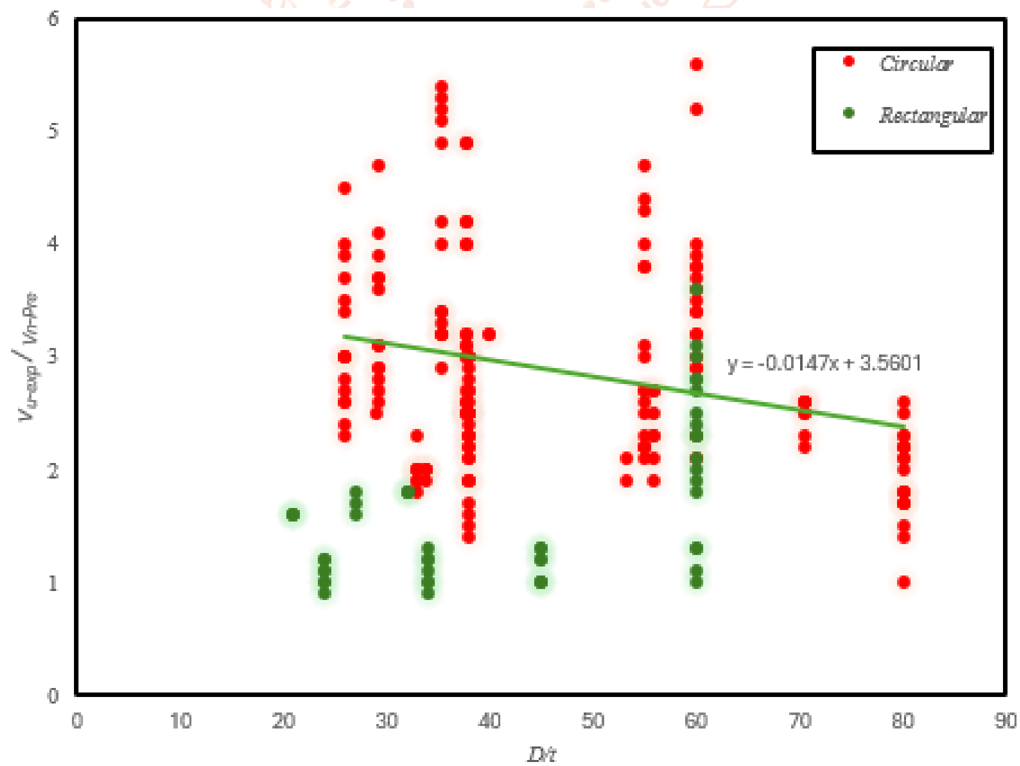

Figure 6 Depth to Thickness Ratio (D/t) Versus (Vexp//Vn).

This figure shows the relationship between shear strength and D/t ratio for CFST samples with different geometries, circular and rectangular sections. However, based on the number of samples in Figure 6, no relationship between shear strength and D/t ratio could be established. To further investigate shear behaviour, Zhang, X., et al(Zhang, Zhao et al. 2023). conducted a parametric study which showed the importance of height-to-thickness ratio (h/t) in predicting the contribution of concrete fill to shear resistance. The study found that h/t ratio affects the shear strength of CFST. Lower h/t ratios were found to increase the normalized contribution of concrete fill, emphasizing its role in improving overall shear resistance. The study also highlighted the need to include h/t ratio in design equations to improve shear resistance predictions. By doing so, engineers can have safer and more efficient designs, avoiding underestimation of shear strength which can lead to structural failure or overestimation which can result to excessive material usage. Overall, the study concluded that including h/t ratio in design considerations provides a better understanding of the interaction between geometry and material properties under shear loads and supports the development of more robust and efficient engineering practices.

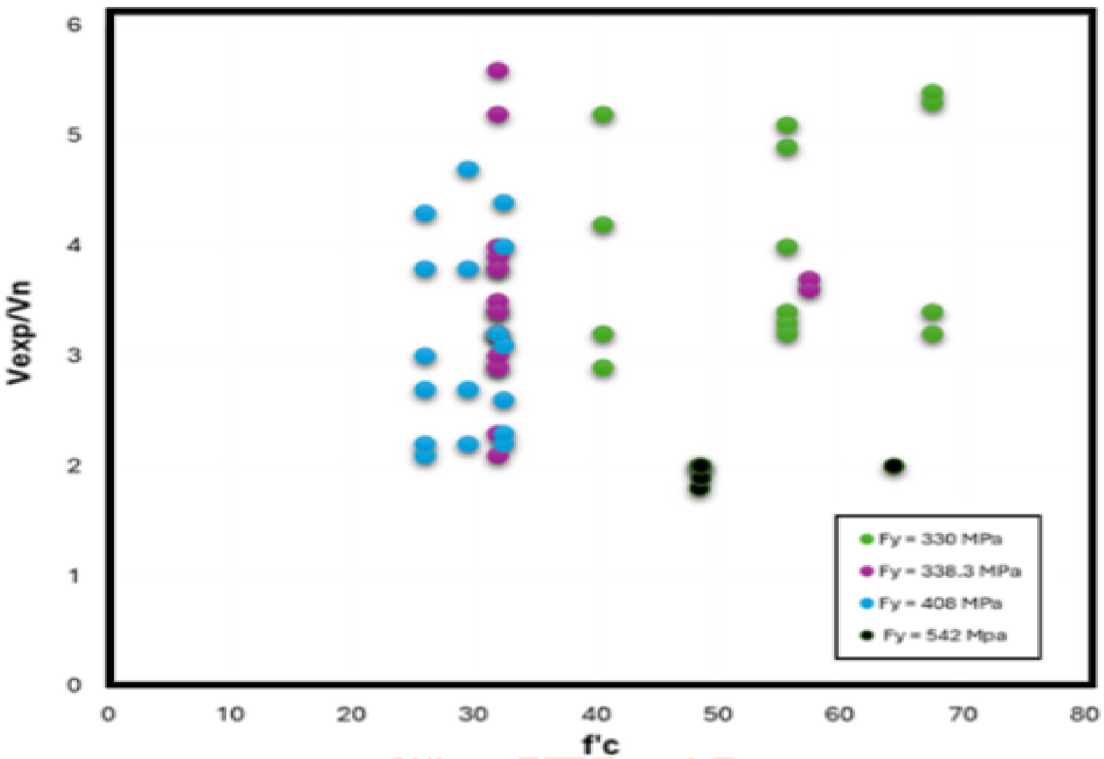

Figure 7 Concrete Compressive Strength (f'c) Versus (Vexp//Vn) of CFST members.

The factors that affect the shear strength of structural elements are investigated by looking at the interaction of key parameters such as concrete compressive strength, steel yield strength and the diameter-to-thickness ratio (D/t). From Figure 6 where the relationship between shear strength and D/t was shown, in Figure 7, the relationship between the shear strength ratio (Vexp/Vn) and concrete compressive strength is shown while steel yield strength (Fy) and D/t are also considered. These specific samples were chosen to study the combined effect of concrete compressive strength and steel yield strength while considering the effect of D/t. From the results, it is seen that the shear strength ratio (Vexp/Vn) varies with steel yield strength and concrete compressive strength. For samples with lower steel yield strength (Fy = 300 MPa and Fy = 338.3 MPa), the green and purple points, the shear strength ratio has a wider range and generally higher values compared to samples with higher steel yield strength (Fy = 408 MPa and Fy = 542 MPa), the blue and black points. This means lower steel yield strength allows the concrete compressive strength to have more effect on the shear capacity. Also, the black points (Fy = 542 MPa) have a more concentrated and lower range of shear strength ratios. This means as steel yield strength increases, the concrete compressive strength has less effect on the overall shear capacity. This is what is expected as higher steel yield strength provides more resistance to deformation and less dependency on concrete compressive properties.

Conclusion.

The study of shear behaviour in concrete filled steel tubes (CFST) shows that geometric, loading and axial parameters play a crucial role in their performance. The study looks at all the factors that affect the shear behaviour of concrete filled steel tubes (CFSTs) and the effect of geometric and material properties on them. Several key parameters such as diameter to thickness ratio (D/t), cross sectional shape, shear span to depth ratio and axial loading conditions were studied to understand the CFST shear resistance mechanisms. The results show that D/t ratio has a significant effect on the shear strength of CFSTs and therefore it should be included in the design equations. By including the D/t ratio in the shear resistance prediction, a better understanding of the interaction between geometry and material properties under shear loads can be achieved and more reliable and efficient engineering practices can be followed. The experimental results also show the effect of cross-sectional shape on CFST shear behaviour. Circular CFSTs outperform square CFSTs in terms of shear strength due to their better confinement and uniform stress distribution. This advantage allows circular CFSTs to resist more shear forces and are more suitable for applications that require higher shear performance. But square CFSTs are still viable in scenarios where their limitations can be mitigated by proper design and material optimization. The shear span to depth ratio also plays a crucial role in determining shear behaviour. Increasing the ratio reduces the shear strength for both circular and rectangular CFSTs. But circular CFSTs perform better due to their better confinement mechanisms. These results show that both cross sectional geometry and shear span to depth ratio should be considered during the design process to get the optimal shear resistance. Also, the axial loading conditions show that circular CFSTs perform better in shear. The circular cross sections provide better confinement to the concrete and steel and hence better utilization of the concrete and steel and higher and more consistent shear strength. Rectangular CFSTs show reduced shear resistance and more variability under axial loading and therefore require cautious design approach when using noncircular sections. This study shows the complex interaction between geometric and material properties in determining the shear behaviour of CFSTs. Circular CFSTs perform better due to their better confinement and stress distribution mechanisms and are the preferred choice for applications that require high shear resistance. But the results also show that square and rectangular CFSTs can be used when their limitations are addressed through proper design. These results can be used to optimize CFST design in practical applications and can lead to more robust and efficient structural solution

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