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Case study

Characteristics of CFRP strengthened masonry wallettes under concentric and eccentric compression

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ABSTRACT

Strengthening of masonry walls using Fibre Reinforced Polymers (FRP) sheets have shown to improve the lateral (in-plane and out-of-plane) resistance and deformation characteristics. While the improvements in shear and flexural resistances of FRP strengthened masonry are well understood, their simultaneous influence on the compression resistance of the masonry is not well explored. Therefore, this study aimed to understand the contribution of Carbon Fibre Reinforced Polymer (CFRP) strengthening on the concentric and eccentric compression strength and deformation characteristics of masonry wallettes. Two types of clay bricks were used to construct the masonry wallettes with a commonly used cement-sand mortar. In total, 36 masonry wallettes were experimentally tested under concentric and eccentric compression. The tests results are presented and discussed in terms of observed failure modes, compressive strengths and axial deformation characteristics derived. The failure of the CFRP strengthened wallettes were mainly attributed by crushing failure of masonry. The transverse stain readings of CFRP sheets on the wallettes confirm that the composite action exists in the CFRP strengthened masonry wallettes. Further, CFRP strengthened wallettes tested under concentric compression have shown to improve the compression resistance only about 10–20 %. The stiffness and ductility of the wallettes strengthened with CFRP has improved (20–30 %) compared to the un-strengthened wallettes. Therefore it can be said that, although the CFRP application can improve the shear and flexural resistances, it does not significantly enhance the compressive strength and ductility, as the compression failure was governed by masonry crushing.

1. Introduction

Fibre reinforced polymers (FRP) are widely used as a feasible structural strengthening and retrofitting material due their high tensile strength, higher strength to weight ratio, resistance to corrosion and ease of application compared to other strengthening systems. The relatively weak tensile resistance and ductility characteristics of masonry demand for strengthening against transient action such as earthquakes, cyclones, impact, tsunami and natural disasters. Subsequently, masonry structures can be strengthened using the FRP solutions to improve the lateral loading resistances (in-plane and out-

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of-plane) and ductility against earthquake actions [1–3]. A large amount of research studies were conducted in this regard and they have shown that the FRP strengthening techniques improve the lateral resistance and ductility of masonry [4–9]; given proper bond compatibility is achieved between masonry substrate and FRP sheet [10–16].

Through extensive studies, the contribution of FRP to the lateral resistance and deformation of masonry members have been understood adequately and design guidelines were developed [17,18]. However, the structural response of FRP-reinforced masonry under compressive loading is not well reported in the literature. It could be hypothesised, since masonry is predominantly used as a deadload-bearing element, that the FRP reinforcement, could concurrently influence the compressive capacity and deformation characteristics. Therefore, designing the FRP-reinforced masonry could have to be verified and sometimes improved while considering changes in the compressive strength and deformation characteristics. Consequently, an experimental programme has been carried out to assess the influence of FRP strengthening solutions to the compression resistance of masonry.

The literature review reveals that the several research studies were focused on assessing the confinement effect of masonry columns wrapped with FRPs, however limited attention was paid to walls or masonry wallettes/panels. Krevaikas and Triantafillou [19] tested Carbon FRP and Glass FRP- reinforced (CFRP and GFRP, respectively) masonry columns under uniaxial compression. It was reported that the FRP confinement of masonry columns increased the load carrying capacity by nearly 1.12–3.66 times and the deformation capacity in the means of ultimate strain at failure by 1.2–4 times compared to unconfined masonry columns. Corradi et al. [20] examined CFRP wrapped brickwork columns under compression. Their study revealed that the axial strength of CFRP confined columns increased nearly by 1.67–2.05 with increased stiffness along with ultimate strain capacity. Several more experimental and analytical studies were carried out to investigate the behaviour of FRP confined masonry columns with different masonry materials (Clay, Concrete and Tuff), FRP systems (CFRP, GFRP, and Basalt Fibres (BFRP)) and column types (Solid and Hollow) in the past [21–27]. Also few experimental and analytical studies were carried out on behaviour of FRP confined columns under sustained load or pre-damage states [28,29]. However, the behaviour of masonry wallettes/panels are different to masonry columns and the above mentioned characteristics are not systematically verified on FRP strengthened masonry wallettes/panels under compression.

Apart from many studies dedicated on FRP application to masonry columns, very few countable studies have been carried out on masonry walls/panels/wallettes on the perspective of examining the influence of FRP application to the compression resistance. Valluzzi [30] used CFRP bars inserted into mortar bed joints to improve the compression capacity and creep of masonry, the experiments showed that this technique reduced the transverse dilation of masonry due to compression stresses, as the bars bear the tensile stresses otherwise bared by the bricks in masonry. Oliveira et al. [31] used similar technique along with grout injection to examine the compressive behaviour of three-leaf stone masonry. The results showed that the technique has increased the compression capacity of stone masonry.

The effect of GFRP reinforced masonry wallettes under compression perpendicular and parallel to the bed joints have been assessed by Prakash and Alagusundaramoorthy [32]. The compression strengths perpendicular and parallel to the bed joints increased nearly by 20 % and 5 %, respectively. Similarly, the corresponding stiffnesses were increased about 110 % and 43 % under compression perpendicular and parallel to the bed joints. Luccioni and Rougier [33] used transverse CFRP strips to laterally confine the masonry wallettes and tested under compression. It was revealed that the applied transverse CFRP strips did not significantly increased the compressive capacity; however increased the axial deformation capacity by nearly 240 %. Further Prakash et al. [34] investigated compressive behaviour of GFRP wrapping to soft brick masonry prisms and showed that the technique could be used to increase the compression capacity of low strength masonry assemblies. A study by Brencich and Gambarotta [35] has shown that the FRP strengthening to masonry prisms contribute to increase the compressive resistance and the corresponding ductility. Recently, Witzany et al. [36] investigated the effectiveness of using CFRP strips applied transversely to the masonry walls and mainly concluded that careful tender of CFRP strips on masonry walls are needed as the load carrying capacity and deformation are influenced by the bond between FRP and masonry assembly, otherwise it was mentioned such strengthening technique may be ineffective.

Hence, it can be highlighted that existing literature on the influence of FRP strengthening technique on the compressive resistance and deformation characteristics lack clarity, where some studies indicate the compressive strength can be improved and other studies revealed the strength enhancement is insignificant. Therefore, in order to better understand the influence of FRP strengthening on the compressive strength and deformation characteristics of masonry, an experimental programme has been designed and implemented. Consequently, the CFRP was selected and applied on masonry wallettes as the FRP strengthening material in this research. In total, 36 masonry wallettes were tested under concentric and eccentric compression in this research. The results are presented in terms of reported failure modes, strengths, axial stress-strain behaviour and moment curvature responses obtained in the experiment and influence of the CFRP application on the compressive resistance and deformation characteristics are discussed.

2. Experimental programme

The experimental programme involved testing of 36 masonry wallettes (18 un-strengthened and 18 CFRP strengthened) under concentric and eccentric compression. Initially, the constitutive materials used in the research (clay bricks, mortar and CFRP) were characterized. Thereafter, construction of the masonry wallettes, application of CFRP and the testing procedures are explained in the following sub-sections.

2.1. Units

Two types of solid clay bricks were used to construction masonry wallettes. These bricks were purposely selected to cover the range of compressive strengths that are commonly available for the local construction in Sri Lanka. The two types of clay bricks are designated as B1 and B2. The density, compressive strength, modulus of rupture, elastic modulus and water absorption were determined and presented in Table 1. Six specimens were tested to determine each property. The coefficients of variation of brick testing results are given within the parentheses. It can be seen that the dimensions of these bricks are more or less same, however their mechanical properties are significantly different, as the B1 brick was a low kiln fired brick corresponds to category II manufacturing and B2 corresponds to quality controlled category I manufacturing as per BS EN 1996-1-1 [37], thus their mechanical properties are significantly different. Further no standards specifically outline the method of determining the elastic modulus of masonry units. Therefore, elastic moduli of the selected bricks were determined while conducting compression tests using clip gauges attached on the face side of the bricks as shown in Fig. 1 to capture the axial deformation on the brick and to compute the elastic moduli of the bricks. The elastic stress was considered as one-third of the peak stress of the stress-strain curve of clay bricks. The elastic strain was taken as the corresponding strain measured at one-third of the peak stress.

2.2. Mortar

Only one type of mortar designation is used in constructing the masonry wallettes. Different types of mortars were not considered as a variable in this study as there are plenty of studies related to influence of mortars to the compressive strength of masonry in the past [42–47]. Ordinary Portland Cement (OPC) was used as the binder in the mortar, which is classified as CEM I 42.5 N of BS EN 197-1 [48]. Mortar mix proportion of 1:5 (binder to sand) by volume was used to construct the masonry wallettes. The mortar mix was prepared based on the flow table consistency of 150 mm. The mean density, water absorption, compressive strength, elastic modulus and flexural strength of the mortar were determined at 28th day of casting and presented in Table 2. Six specimens were tested to determine each property of the mortar mixes. The mortar cylinder dimensions were 100 mm (diameter) and 200 mm (height). The mean compressive strengths of mortar determined through prism halve and cylinder samples are 6.6MPa and 4.7 MPa respectively. Further, using the extensometers, the deformation of the mortar cylinders were recorded as show in Fig. 1(b). Afterwards using the stress-strain curves of the mortar, the elastic moduli were computed and reported in Table 2.

2.3. CFRP

The unidirectional CFRP sheet with epoxy resin strengthening system was used to apply on the masonry wallettes. The basic properties of the CFRP used in the research programme were obtained from the manufacturer's datasheet. The unit weight (weight of unit surface), density and design thickness of the CFRP were 230 g/m^2, 1.77 g/m^3 and 0.17 mm, respectively.

Only the uniaxial tensile strength of the CFRP sheets was experimentally verified as shown in Fig. 1(c). The testing was based on the ACI 440.2R-08 [54] and performed at a displacement control loading rate of 0.5 mm/min in the 1000 kN universal testing machine. The elongation of the CFRP was measured using a strain gauge. Three samples were tested to get the average values of the tensile strength and elastic modulus of the CFRP used in this research. Rupture failure of CFRP was primarily reported under axial tension. The average tensile strength of 1465 MPa with COV of 6.5 % and elastic modulus of 71 MPa with COV of 14.4 % were determined. The properties of resin were also obtained from the datasheet of the manufacturer. The specific gravity, geltime, and flexural strength were 1.8, 80 min, and 60 MPa respectively.

2.4. Wallette construction

Masonry wallettes were constructed and tested as per BS EN 1052-1 [55]. In total, 36 wallettes were constructed and tested with two types of clay bricks, and with and without CFRP application on the face sides of the masonry wallettes surface, similar to the application on the masonry walls. Subsequently, three wallettes were tested per each combination. All the masonry wallettes were eight unit courses high and two courses wide with two brick thickness. The wallettes were constructed with Flemish bond pattern. The wallettes were constructed by an experienced mason and 10 mm mortar joints were maintained.

The CFRP application process was made after 14 days of the construction of wallettes. To apply the CFRP sheet, the face sides of the masonry wallettes were cleaned by sand paper to remove any excessive hardened mortar from the joints and loose particles on the surface. Wet layup technique was used to bond the CFRP sheet to masonry. A thick layer of two component saturating epoxy resin was applied on the masonry surface using paint roller as shown in Fig. 2(a). Then the CFRP sheets that were cut to the required dimensions, later were pressed and pasted on the masonry surface as presented in Fig. 2(b). The uni-directional CFRP sheets were applied horizontally to the wallettes, where the fibres are oriented parallel to the bed joints of the masonry. Then the paint roller was used to remove the entrapped air between CFRP sheet and masonry surface by rolling over with gentle pressure.

The complete test matrix is given in Table 3. Fig. 2(c) shows the CFRP strengthened masonry wallettes. It has to be noted that the CFRP sheets were applied only to the face sides of the wallettes, and not fully wrapped, to investigate the

Table 1
Properties of Clay Bricks.

Unit type	Dimension/ (mm) (L × W×H)	Density/ (kg/m^3) BS EN 772-13 [38]	Compressive Strength/ (MPa) BS EN 772-1 [39]	Modulus of Rupture/ (MPa) BS EN 772-6 [40]	Water absorption/ (%) BS EN 772-11 [41]	Elastic Modulus/ (MPa) –
B1	200 × 95 × 65	1757 (4.1)	4.05 (10.5)	0.71 (9.7)	11.3 (10.1)	3856 (8.7)
B2	210 × 100 × 60	2218 (6.9)	17.3 (8.9)	2.83 (9.3)	6.3 (7.6)	10122 (9.4)

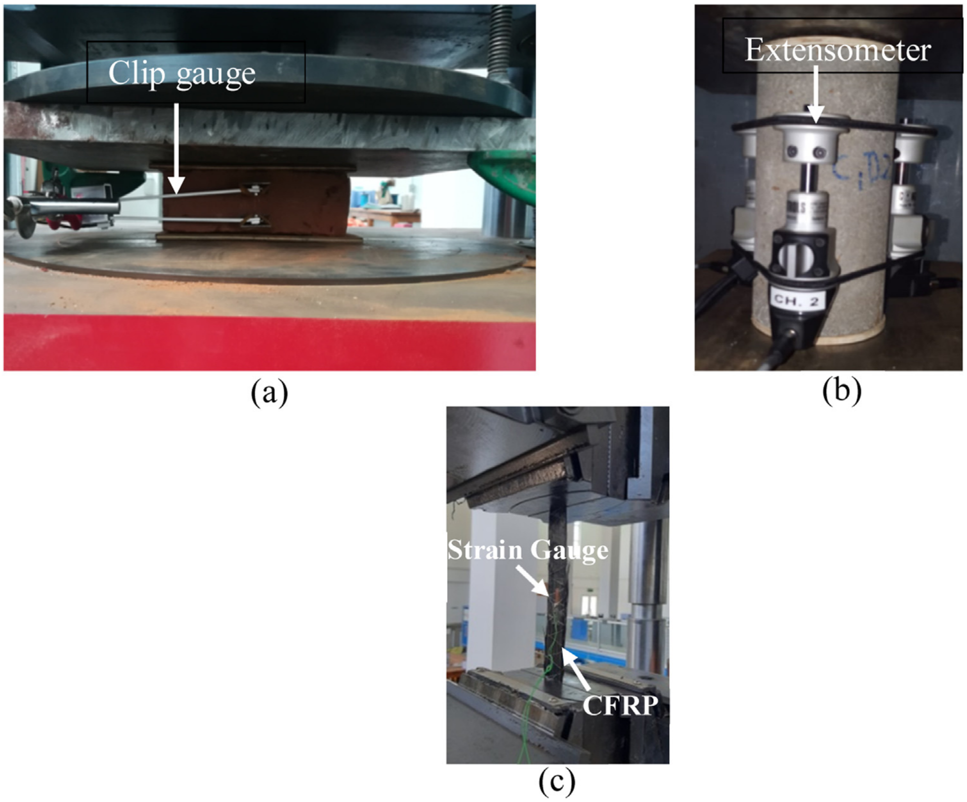

Fig. 1. Material characterisation (a) brick compression testing (b) mortar compression testing and (c) tensile testing of CFRP.

Table 2
Properties of cement mortar.

Density/ (kg/m^3)	Consistency/ (mm)	Water absorption/ (%)	Prism Compressive Strength/ (MPa)	Flexural strength/ (MPa)	Cylinder Compressive Strength/ (MPa)	Secant Modulus/ (MPa)
BS EN 1015-10 [49] 1869 (0.7)	BS EN 1015-3 [50] 148 (11.2)	BS EN 1015-18 [51] 8.5 (3.4)	BS EN 1015-11 [51] 6.6 (7.7)	BS EN 1015-11 [52] 0.42 (8.4)	ASTM C780 - 19 [53] 4.71 (10.4)	– 3325 (9.9)

effectiveness of conventional shear strengthening method of CFRP application to the masonry walls. Furthermore, two eccentric loading conditions were adopted. Based on the width of the wallettes (i.e. 200 mm and 210 mm for B1 and B2 series wallettes), the relative eccentricities of 0.13 and 0.33 were considered for the testing. Higher values of eccentricities were not considered as they are unlikely occur in the real construction practices. The relative eccentricity is defined as the ratio between the distances of load application from the center of gravity of the section to the distance of the edge of the section along the eccentric loading direction, where the load applied. The eccentric loading condition is schematically illustrated in Fig. 3(a) and (b).

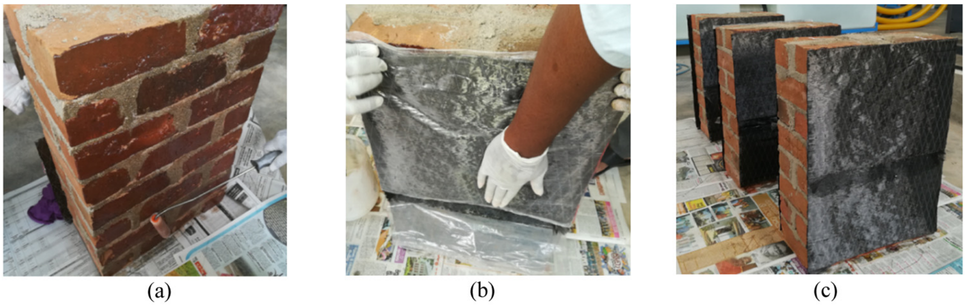

Fig. 2. CFRP application processes on the masonry wallettes (a) application of epoxy resin on masonry (b) pasting of CFRP sheets on masonry surface and (c) CFRP strengthened masonry.

Table 3
Experimental test matrix.

Notation	Brick type	Wallette dimension (mm)	Strengthening type	Type of loading	Relative eccentricity	Specimens tested
B1-U-C-0	B1	410 × 200 × 590	U	C	0	3
B1-S-C-0		(length × width × height)	S	C	0	3
B1-U-E-0.13			U	E	0.13	3
B1-S-E-0.13			S	E	0.13	3
B1-U-E-0.33			U	E	0.33	3
B1-S-E-0.33			S	E	0.33	3
B2-U-C-0	B2	430 × 210 × 550	U	C	0	3
B2-S-C-0		(length × width × height)	S	C	0	3
B2-U-E-0.13			U	E	0.13	3
B2-S-E-0.13			S	E	0.13	3
B2-U-E-0.33			U	E	0.33	3
B2-S-E-0.33			S	E	0.33	3

An alphanumeric notation is used denote each testing combination. B1 and B2 are used to denote the type of brick used, followed by a letter indicates whether the wallettes are strengthened or not (U-unstrengthened and S-strengthened), the forth letter indicates the type of loading (C-concentric and E-eccentric) and the final number gives the relative eccentricity applied (0.13 and 0.33).

2.5. Test set-up

The compression testing was carried out on a servo-controlled universal testing machine (UTM) with a maximum loading capacity of 1000 kN. The upper plate of the UTM was hinged to avoid loading misalignment. The wallettes were aligned carefully between the platens of testing machine to avoid any accidental eccentricity for the concentric loaded combinations. Further to reduce platen restrain effect between loading steel plate and masonry, 5 mm plywood capping was placed on the top and bottom bed faces of the wallettes. The compression testing was carried out at constant displacement controlled mode (i.e. 0.25 mm/min) to capture the complete post-crack behaviour of masonry wallettes tested under axial compression. Displacement transducers were attached on the specimens to capture the vertical deformation of the wallettes under compression as shown in Fig. 3. In total, four displacement (two per face) transducers (LVDTs) were used to capture the vertical deformation of the wallettes and another two (one per face) were used to measure the lateral deformation at the mid-height. Furthermore, two strain gauges (one per face) were pasted to measure the lateral strain development on the CFRP sheets at the mid-height of the wallettes as indicated in Fig. 3(c) and (d). The average deformation measurement was taken to eliminate any possible eccentricities in the height and thickness directions of the wallettes. The loads and displacements/strains were measured and recorded using a synchronised data acquisition system.

The eccentric compression testing loading was carried out by applying the axial load using cylindrical rollers on top and bottom as shown in Fig. 3(b). Further, 50 mm thick steel plates were placed between the rollers and wallettes to uniformly

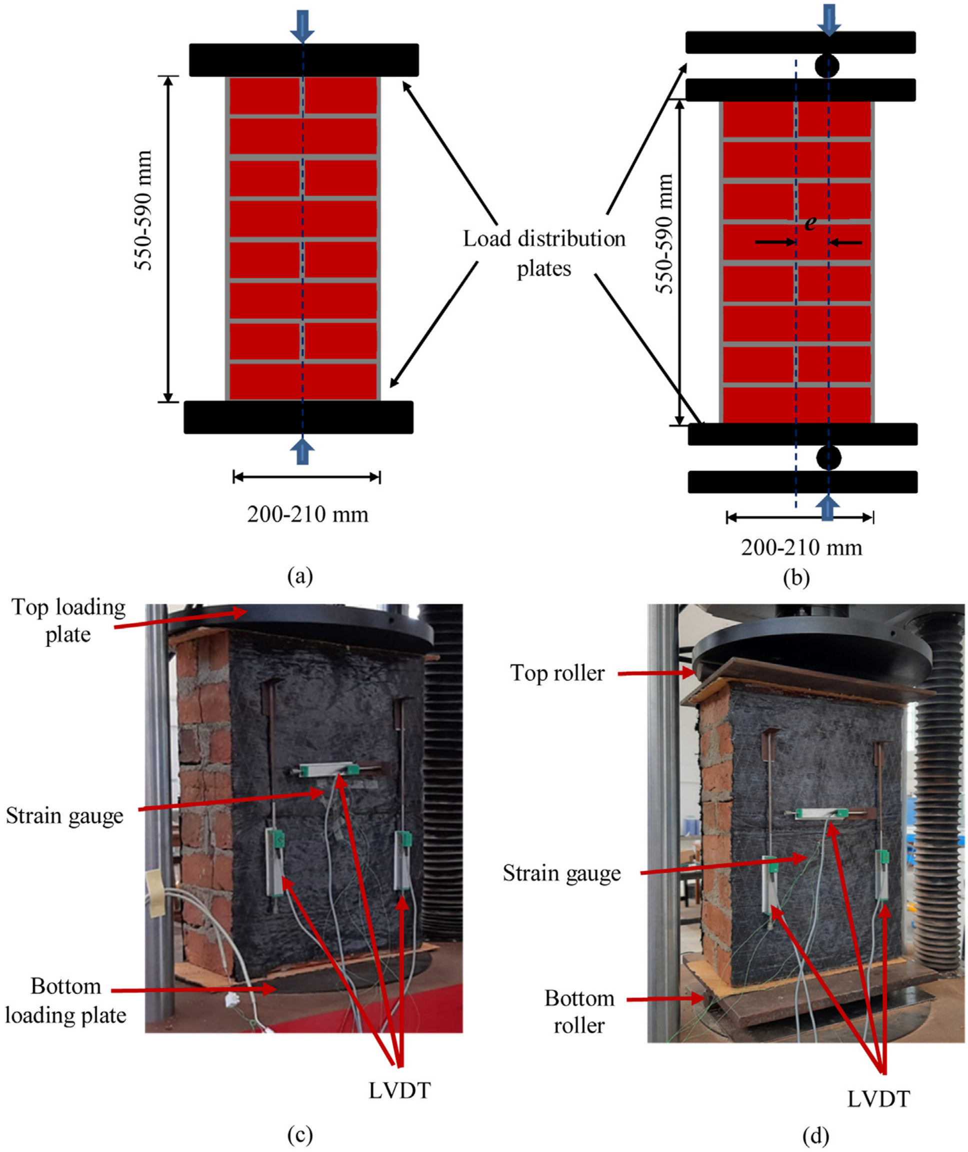

Fig. 3. (a) Diagram of concentric loading set-up (b) Diagram of eccentric loading set-up (c) Concentric loading testing and (d) Eccentric loading testing.

distribute the eccentric load on the cross section. This eccentric loading arrangement warranted the constant eccentricity throughout the height of the wallettes.

3. Results and discussion

The experimental results of the wallettes tested under concentric and eccentric compression loading are presented and discussed in the following sub-sections.

3.1. Failure patterns

The typical failure patterns of concentric loaded wallettes tested without and with CFRP strengthening are shown in Fig. 4. Commonly, the cracks initiated at about 70 %–80 % of the peak load and the nonlinear behaviour of the load displacement behaviour was associated with the propagation of the initial cracks. The ultimate failure patterns of the un-strengthened B1-U-C-0 and B2-U-C-0 wallettes were mainly characterised with parallel vertical cracks on all the sides of the wallettes, which were originated at brick to mortar interfaces and propagated through the middle of the bricks. Similar behavior was found in the experimental studies reported in the past [56–59]. Further as CFRP sheets were covered on the face

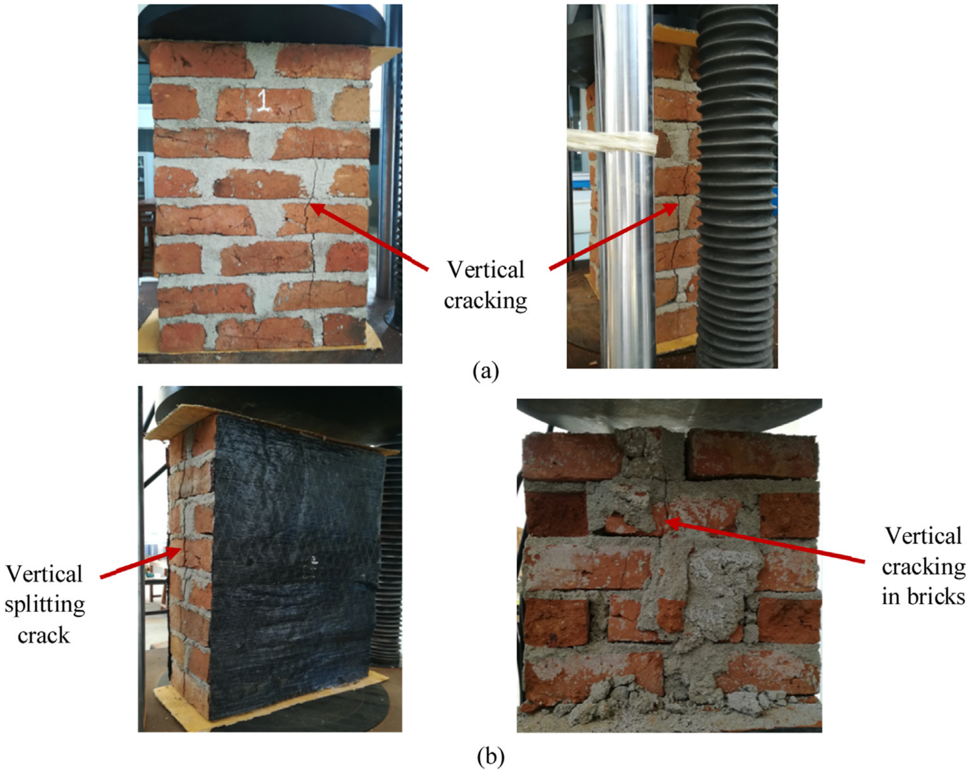

Fig. 4. Failure patterns of concentric loaded wallettes (a) Un-strengthened and (b) Strengthened.

sides of the wallettes, no visible cracks were noted for the B1-S-C-0 and B2-S-C-0 under concentric compression. However those wallettes have shown predominantly single splitting cracks on the short sides and no rupture of the CFRP was noted in the testing. Moreover, the inspection of the those split wallettes as shown in Fig. 4(b) have revealed that the bricks were cracked inside on the face sides, however the CFRP application on those surfaces has prevented the degradation of the bricks and held them even after cracking.

Further, the failure of un-strengthened wallettes under eccentric compression were characterised by splitting cracks developed on the sides as shown in Fig. 5(a), also the compression face sides of the wallettes depicted conventional vertical parallel cracks as the failure is described by dilation of masonry under compression. Further, on the tension face side of the wallettes portrayed slight opening of mortar joints due to tensile bond failure between unit and mortar. The eccentrically loaded CFRP strengthened wallettes showed mainly splitting cracks on the un-strengthened sides as shown in Fig. 5(b). No visible ruptures of CFRP sheets were noted on the compression or tension faces of the wallets.

3.2. Concentric compressive response

Table 4 presents the mean concentric compressive strengths and deformation parameters such as elastic moduli, Poisson's ratios, peak strains and ultimate strains obtained. The COVs of the parameters are given in parentheses. The compressive strength was calculated by dividing the measured peak load by loaded area (bedded area) of the wallettes. Obviously the B2 series wallettes have shown higher compressive strength than the B1 series wallettes as the strength of the B2 brick was higher than the B1 brick, thus the unit strength mainly governs the compressive strength of masonry. Further, it can be noted that the strength increment in strengthened wallettes are around 20 % compared to the corresponding un-strengthened wallettes, thus it can be mentioned that the no significant change in compressive strengths between strengthened and un-strengthened wallettes were found.

The lack of compressive strength enhancement in CFRP strengthened on masonry wallettes or subsequently to the masonry panels/walls could be due to the unconfined state of masonry in CFRP sheets on walls, unlike FRP strengthened/ confined to masonry columns. The failure modes of strengthened wallettes under concentric compression justify the argument, where it was mainly attributed by the crushing of masonry. The cracks were predominantly developed on the un-strengthened sides of the wallettes and the ultimate failure was due to the splitting of the wallettes into two halves (sideways). Even through CFRP sheets was able to contain the crack development on the face sides of the wallettes under compression, the unconfined sides of the wallette followed similar failure pattern as of the un-strengthened wallettes. The average lateral strains measured on the CFRP sheets were 2374 $\mu\varepsilon$ and 1953 $\mu\varepsilon$ for B1 and B2 series wallettes tested under

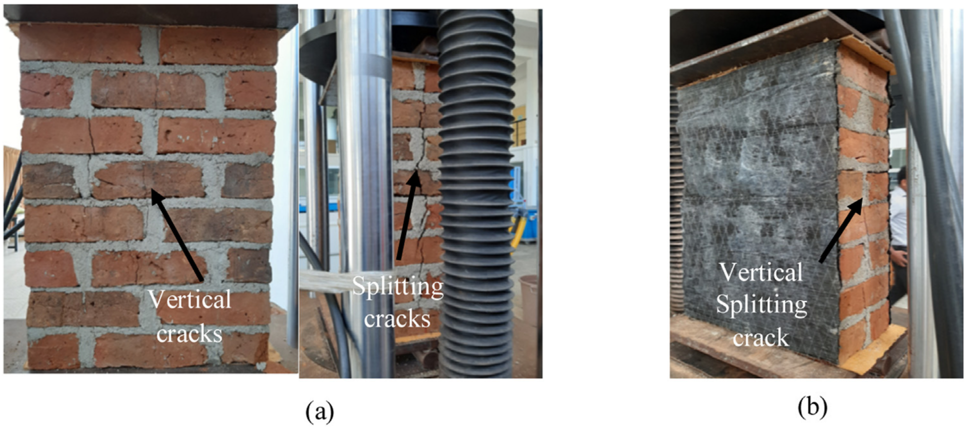

Fig. 5. Failure patterns of eccentric loaded wallettes (a) Un-strengthened and (b) Strengthened.

Table 4
Strength and deformation characteristics of concentrically loaded wallettes.

Notation	Peak load (kN)	Compressive Strength (MPa)	Elastic Modulus (MPa)	Poisson's Ratio	Peak Strain	Ultimate Strain	Ductility
B1-U-C-0	99.4 (13.0)	1.23 (12.5)	710 (17.1)	0.21 (3.4)	0.0025 (9.9)	0.0027 (9.9)	1.84 (5.5)
B1-S-C-0	123.6 (11.6)	1.46 (11.5)	812 (5.6)	0.16 (14.4)	0.0027 (9.3)	0.003 (5.3)	2.01 (4.6)
B2-U-C-0	554.6 (9.5)	6.76 (9.2)	5074 (5.4)	0.18 (5.3)	0.0016 (14.8)	0.0018 (8.8)	1.82 (15.2)
B2-S-C-0	596.2 (9.8)	7.49 (9.6)	5814 (7.2)	0.15 (11.7)	0.0019 (2.5)	0.0021 (11.7)	1.93 (12.4)

concentric loading respectively, which were less than the rupture strain of the CFRP. Therefore, it could be postulated the FRP strengthening of masonry would not significantly enhance the compressive resistance as the whole wall cannot be fully confined, unless some anchoring mechanism is developed to confine the thickness direction of the walls as well.

The compressive stress-strain curves of the concentrically loaded un-strengthened and strengthened wallettes are shown in Fig. 6. The three curves in every plot in Fig. 6, refer to the three specimens tested in each combination. The measured axial displacements were divided by the gauge length (across one half of the wallette height) to calculate the axial strain values and matched with the corresponding stress values computed from the load measurements to plot the stress-strain curves of the wallettes. It can be seen that the stress-strain curves of all the un-strengthened wallettes follow similar tread, despite the change in brick types. Generally, the wallettes displayed approximately linear stress-strain behaviour up to 60–70 % of the peak strength and afterward nonlinear behaviour was observed up to the failure. Three distinct regions can be noted in the stress-strain curves (1) initial linear elastic region (2) non-linear pre peak hardening region and (3) non-linear softening region. The nonlinear behaviour was largely related with the initiation of vertical cracking in the wallettes. Furthermore, it can be noted that the stress-strain curves were obtained up to nearly 20–30 % drop of peak stress in the post peak region. The reason for variation in the post peak response is largely associated with the failure nature and most of the testing was stopped after observing severe cracking and spalling of masonry pieces that influenced the post peak stress-strain responses of the wallettes.

Further, the low strength B1 brick series wallettes have shown higher deformability than the relatively high strength B2 series wallettes as the axial deformation capacity of the B2 brick was less than B1 brick. Therefore, it can be said that the brick strength and its deformation properties significantly influence the overall stress-strain behaviour of masonry under compression.

The stress-strain curves of strengthened wallettes under concentric compression are slightly different to the un-strengthened wallettes, where there was a break in the stress-strain curve associated with the splitting of wallettes into two halves. Thereafter the split two halves of the wallette behaved as individual columns and the load increment was noted until the failure of those two halves. This failure pattern was not well observed in the past studies as all the wallettes/panels tested were single brick thickness [60,61]. However, this failure and stress-strain curve phenomena are similar to the un-strengthened masonry wallettes tested under compression parallel to the bed joints, where the failure was through the bed joints and thereafter split masonry halved behaviour as individual components, readers can refer more details on this regard from Dhanasekar et al. [62] and Thamboo and Dhanasekar [63].

The average deformation characteristics of the masonry wallettes (1) elastic modulus, (2) Poisson's ratio (3) peak strain (4) ultimate strain and (5) ductility were determined from the stress-strain curves. The elastic moduli of the masonry wallettes were determined at the one-third of the peak stresses and corresponding elastic strains were matched in the stress-strain curve. The Poisson's ratios were computed from the elastic axial strain values and the corresponding lateral strain values. The peak strain was determined conforming to the peak stress of the tested wallettes. The ultimate strain was

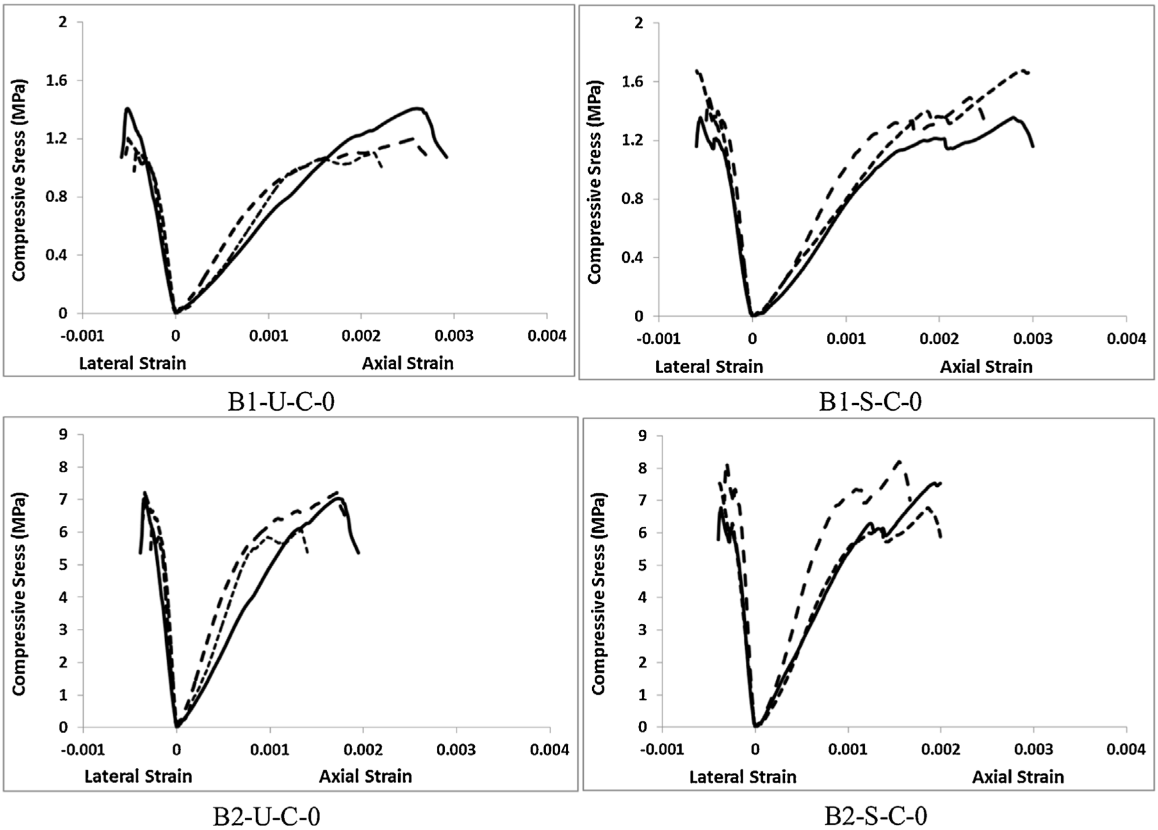

Fig. 6. Axial stress-strain responses of concentric loaded wallettes.

acquired corresponding to the 80 % of the post-peak stress. Further, the ductility of the wallettes under compression loading were determined as per the method proposed by Muguruma et al. [64] and Thamboo and Dhanasekar [65], where the stress-strain curve was idealised as an elastic-perfectly-plastic curve. The yield strain corresponds to the intersection of the bi-linear approximation. The ratio between the ultimate and the yield strain was defined as the ductility.

It can be noted that there is a marginal increment (~10 %) in elastic moduli between un-strengthened and strengthened wallettes. Further, it can be noted from peak and ultimate strain values of strengthened wallettes have shown slightly more deformation than the un-strengthened wallettes. Therefore, overall the CFRP application on the wallettes on both faces has minimal influence on the strength and deformation characteristics of masonry wallettes under concentric compression.

3.3. Eccentric compressive response

It has to be mentioned that the behaviour of the eccentric loaded wallettes are not treated in terms of stress-strain responses, as the wallettes were not subjected to uniform stresses, therefore they are presented and discussed in terms of moment-curvature responses. Thus, the moment-curvature responses were derived by using the load-displacement responses of the wallettes tested under eccentric loading and schematically illustrated in Fig. 7. The moment was obtained by multiplying the load measurements by the eccentricity applied, while the curvature (ϕ) was calculated by dividing the mean strain on each face of the wallettes by the corresponding thickness of the masonry. Cavaleri et al. [66] and Cevallos [67] explained similar method of developing the moment-curvature curves, where h_{ef} and b are the height and thickness of the wallette. The h_1 and h_2 are the gauge lengths used for the axial vertical deformation measurement, subsequently the Δh_1 and Δh_2 are the axial deformation measured.

Figs. 8 and 9 present the moment-curvature responses of the B1 and B2 series wallettes subjected to eccentric loading, respectively. The three curves in every plot in Figs. 8 and 9, denote to the three specimens tested in each combination. The critical load, moment and rotation capacities derived from the eccentric loading conditions from the testing data are presented in Table 5. The peak load was taken as the maximum load reached in the eccentric testing data for each wallette testing combinations. The peak moment capacity corresponds to the multiplication of peak load by the respective eccentricity applied. The peak curvature (ϕ_{peak}) was taken as the curvature value that corresponds to the peak moment capacity. The reductions in eccentric load compared to the relevant concentric loaded wallettes also given in the Table 5. The ductility of the eccentric loaded wallettes was determined as similar to the concentric loaded wallettes. However, instead of

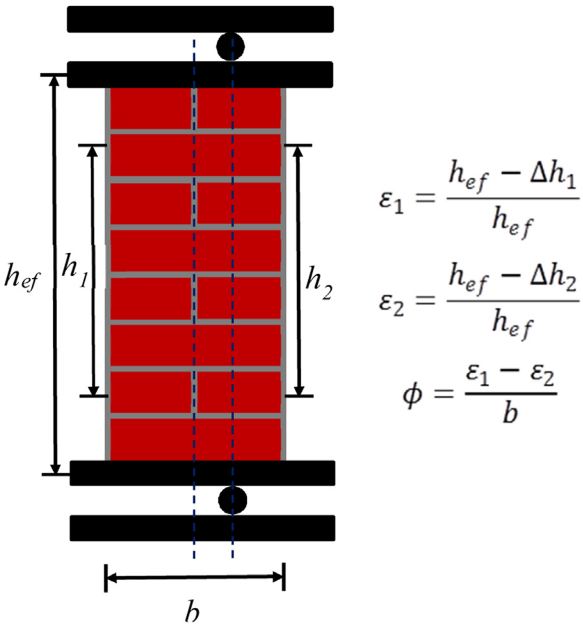

Fig. 7. Scheme for the calculation of the curvature.

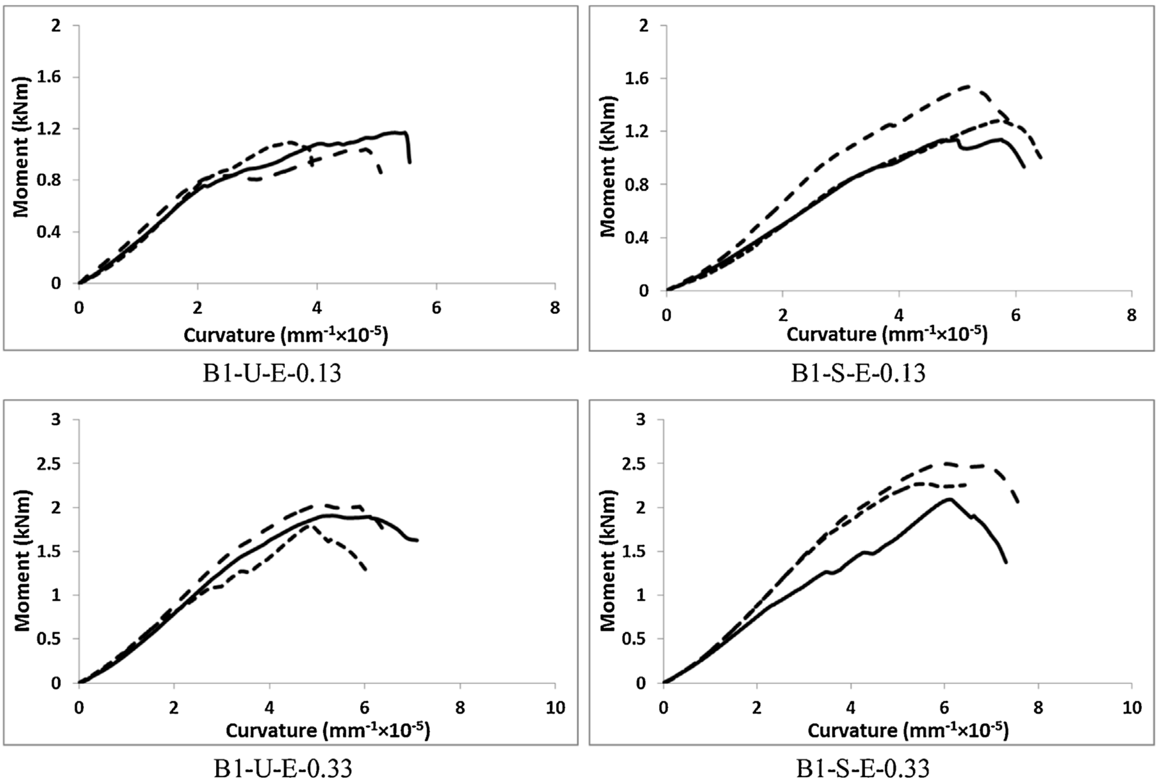

Fig. 8. Moment-curvature response of eccentrically load B1 series wallettes.

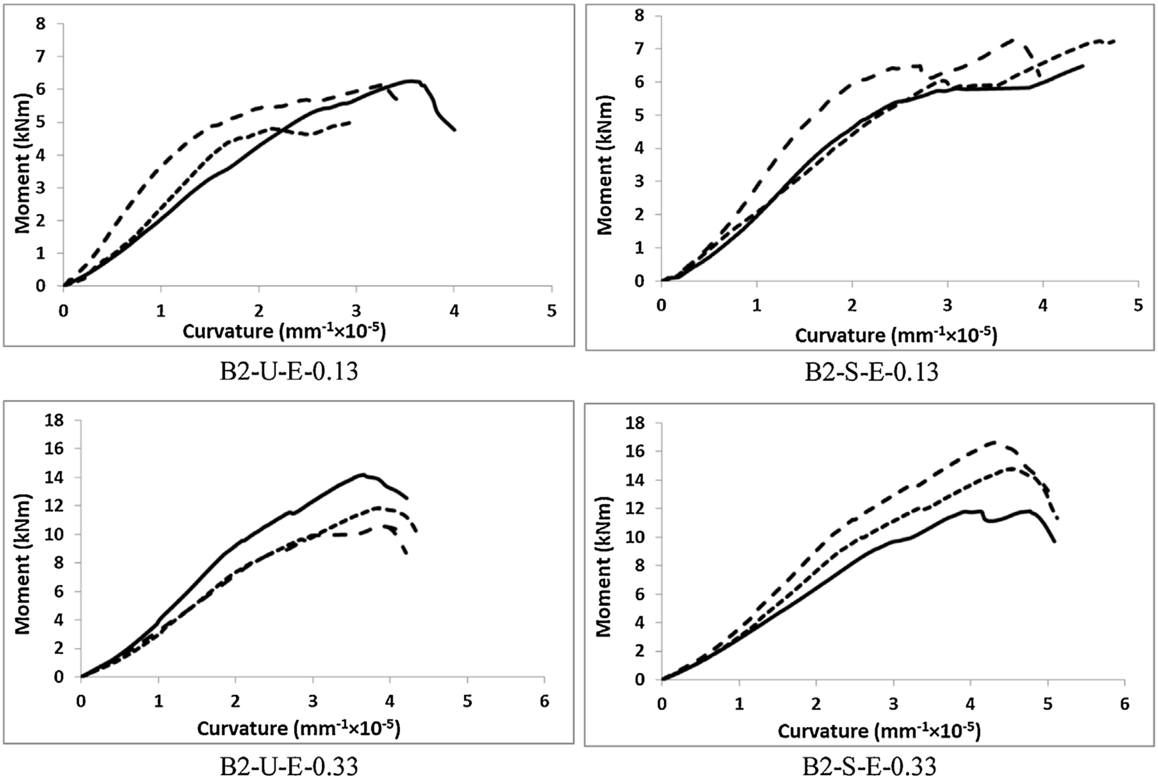

Fig. 9. Moment-curvature response of eccentrically load B2 series wallettes.

Table 5
Strength and deformation characteristics of eccentrically loaded wallettes.

Notation	Peak load (kN)	Load reduction percentage (%)	Peak moment (kNm)	Change (%)	Φ_{peak} (mm^{-1}×10-^{5})	Ductility
B1-U-E-0.13	84.5 (5.7)	15.5	1.1 (5.7)	11.5	4.5 (12.5)	1.32 (3.9)
B1-S-E-0.13	104.2 (15.2)	13.0	1.4 (15.2)		5.6 (5.7)	1.53 (8.5)
B1-U-E-0.33	56.8 (6.6)	43.2	1.8 (10.3)	25.0	5.3 (4.6)	1.38 (5.1)
B1-S-E-0.33	69.1 (9.1)	43.9	2.3 (9.1)		6.1 (10.4)	1.48 (4.5)
B2-U-E-0.13	440.0 (14.2)	20.6	5.5 (14.2)	15.0	3.3 (7.7)	1.41 (5.7)
B2-S-E-0.13	524.3 (11.4)	17.0	6.8 (11.4)		4.3 (9.4)	1.84 (9.2)
B2-U-E-0.33	369.4 (14.7)	33.4	12.2 (15.8)	18.0	3.8 (3.9)	1.39 (18.2)
B2-S-E-0.33	437.8 (16.9)	28.3	14.4 (16.9)		4.6 (5.3)	1.51 (7.3)

yield and ultimate axial strains, the yield and ultimate curvature points were taken to calculate ductility in the eccentric loaded conditions.

It can be obviously noted as the eccentricity increases the peak load of the wallettes reduces despite of CFRP strengthening. The reduction in the load carrying capacities of the different wallette combinations tested vary between 15.5 %–24 % for relative eccentricity of 0.13 and range between 28.3 %–43.9 % for relative eccentricity of 0.33. However, when comparing the peak load or moment carrying capacities between CFRP strengthened and un-strengthened wallettes, the strengthened wallettes have shown to bear slightly higher load and moment than the un-strengthened wallettes. Thus, the CFRP strengthening is relatively effective in resisting the combined axial and bending stresses in the wallettes. The peak curvature and the ductility values taken from the moment curvature responses curves also indicate that the CFRP strengthening has improved the rotational capacity of the masonry wallettes. Nevertheless, it has to be highlighted that the lack of strength and deformation capacity enhancement could be due to the failure nature of the masonry. Despite of CFRP application on the surface of the wallettes, the masonry still failed through compression crushing, thus the tensile capacity of the CFRP was not fully effective in resisting the bending stressed raised due to eccentric loading.

4. Summary and conclusions

The contribution of FRP strengthening to the in-plane shear and out of flexural behaviour of masonry is well researched; however effect of FRP application on the compression resistance of masonry, which has been used to the strengthen the masonry for shear and flexure is not well explored. Therefore this paper presented the results of an experimental study aiming to investigate the concentric and eccentric compressive strengths and deformation characteristics of masonry wallettes strengthened with CFRP sheets on their face sides. In total, 36 masonry wallettes were tested with and without CFRP application and different compression loading conditions (concentric and eccentric). The experimental results are presented and discussed in terms of failure patterns, compressive strength, stress-strain and moment curvature responses obtained. Based on the results obtained and the variables investigated, the following conclusions can be drawn:

- The strain measurements on the CFRP sheets, especially the lateral strain indicate that the CFRP bonding is effective and the composite action exists in the strengthened wallettes under axial concentric loading.
- The failure patterns of concentric loaded un-strengthened and CFRP strengthened wallettes were mainly characterised by conventional vertical cracking of masonry parallel to the loading direction. No lateral rupture of CFRP was noted.
- The CFRP strengthening has marginally increased ($\sim$10−20 %) the compressive resistance of the masonry wallettes compared to the un-strengthened wallettes. However, the influence of FRP application to masonry wallettes/walls is not as effective as it contribute to the masonry columns with confinement. Also the comparison of elastic moduli, peak strains, ultimate strains and ductility values between the CFRP strengthened and un-strengthened wallettes under concentric loading indicate that the strengthening method has slightly improved the deformation characteristics of the masonry.
- The failure patterns of the un-strengthened wallettes under eccentric loading were attributed by failure of masonry by crushing on the compression side. However the CFRP strengthened wallettes have shown predominantly splitting vertical cracks on masonry on the un-strengthened sides.
- Obviously, the eccentric loading has reduced the load carrying capacity of the wallettes; however the CFRP strengthened wallettes have shown to comparatively carry more loads in the eccentric loading condition than the un-strengthened wallettes. Further, the rotational capacity and the ductility measurements of the eccentric loaded wallettes show that the strengthening method is moderately effective in enhancing the deformation characteristics.

In summary, it can be highlighted even through the CFRP strengthening can be used to increase the shear and flexural resistances, its contribution to improve the compressive resistance is minimal. Nevertheless, in this research, the only the unidirectional FRP sheets were trialled as the strengthening material on masonry surface, however when it comes to the eccentric loading condition, the CFRP alignment should be on both directions on the faces of the wallettes to resist the tensile stresses on the bending side and as well as lateral dilation. Thus, further research studies are needed to investigate the FRP orientation on the compressive characteristics of masonry and also with different FRP systems such as glass, basalt and steel.

CRediT authorship contribution statement

Julian Thamboo: Conceptualization, Funding acquisition, Formal analysis, Data curation, Writing - original draft. **Satheeskumar Navaratnam:** Formal analysis, Data curation. **Keerthan Poologanathan:** Supervision, Writing - review & editing. **Marco Corradi:** Writing - review & editing.

Declaration of Competing Interest

The authors declare there are no conflicts of interest in this research.

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