Evaluation of shear resistance for beam-column connections using ultra high performance steel fibre reinforced concrete (UHPSFRC) under cyclic loading by experimental research

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Evaluation of shear resistance for beam-column connections using ultra high performance steel fibre reinforced concrete (UHPSFRC) under cyclic loading by experimental research

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Abstract. Evaluation of behavior for beam-column connections in the buildings under cyclic loading is extremely important, where shear resistance is one of the important factors. Beam-column connections are considered places in which stresses are concentrated during working process and it is clearly showed in exterior beam-column connections. There have been many published research and experimental investigations for the external beam-column connections. The use of new concrete material (UHPSFRC) for strengthening the external beam-column connections is a new idea and has not been much studied yet. Therefore, this paper presents the experimental investigation results for shear resistance of external beam-column connections followed EuroCode 8 [1] with ductility class high (DCH). This experimental result proposes the idea about strengthening for beam-column connections, provide additional experimental data and help the design process followed seismic specification of Vietnam.

1. Introduction
Beam-column connection is an important part in reinforced concrete frame structures. This part is subjected the full pressure of the building due to loads other factors such as storms, earthquakes, strong winds, ...Therefore, the beam-column connection should be calculated accurately and carefully for ensuring the quality and safety of the structures. In Vietnam, in the standard calculation for reinforced concrete structures, there is no specific method for calculating reinforced concrete beam-column connection in frame structures, especially for high buildings subjected dynamic loads.

During the time of earthquake, the beam-column connections in the frames are usually subjected to greater shear stresses and axial forces than other structural members. The development of principal tensile and compressive stresses leads to the formation of cross cracks and the crushing of concrete in the beam-column connections causing shear failure. Recently, the use of reinforcement techniques has also been applied such as fiber glass reinforced plastic composite material (FRP) [3], HPFRC high-performance concrete coatings [4] or direct pouring of reinforced concrete (FRC) in the beam-column connections in the frames [5] has attracted attention thanks to the outstanding mechanical properties of the material. In 2019, a study by Khan et al. [6] used a 30 mm thick UHPSFRC concrete material reinforced for beam-column connections with epoxy glue, the results showed that the hardness and displacement increased significantly. Based on the above study, this paper proposes the use of ultra-high performance fiber reinforced concrete (UHPSFRC) in order to evaluate the effectiveness of the use of new materials and propose the idea for strengthening of beam-column connections in frame structures designed with high degree of plasticity (DCH).
2. Experimental procedure
The experiment was conducted at LAS XD-01 earthquake research laboratory of the Vietnam Institute for Building Science and Technology (IBST).

2.1. Design of exterior beam-column connections
The study was performed on three experimental samples. The sample S1 is designed according to the Eurocode 8 [1] with a high degree of plasticity (DCH), in the sample S2 the stirrup is completely removed in the beam-column connection area with a distance of 400mm (i.e. at the end of the area D according to Eurocode 2 [7]), in the final sample S3 the stirrup is also completely removed but with a distance equal to the critical length as Figure 1.

![Figure 1. Design detail of samples S1, S2 and S3](image)

2.2. Material grades and mechanical properties
Material grades are based on studies of UHPSFRC materials in Vietnam [8]. In which silica fume component fills the remaining gaps in cement thus reducing porosity [9].

Table 1. Material grades and mechanical properties of UHPSFRC

| Steel fiber content | Material for 1 m³, kg | Mechanical properties |
|---------------------|-----------------------|-----------------------|
|                     | Water                 | Cement                | Silica fume | Sand quartz | Plasticity (%) |  \( f'_c \) (MPa) |  \( f'_{lc} \) (MPa) |  \( E' \) (GPa) |
| 2%                  | 162                   | 886                   | 222         | 1109        | 39.5           | 107                  | 8.1                 | 42                |
| a                   | Fiber diameter \( d_f = 0.2 \)mm, Fiber length \( l_f = 13 \)mm |
| b                   | Cylindrical sample 100 x200mm defined according to ASTM C39 [10]. |
| c                   | Cylindrical sample 100x200mm defined according to ASTM C09 [11]. |
| d                   | Sample directly subjected to tension with cross section 50 x 100 mm and length 500 mm [12]. |
2.3. Setting scheme of experiment and measuring equipment

The experiment was conducted at LAS XD-01 earthquake research laboratory of the Vietnam Institute for Building Science and Technology (IBST). All samples were tested in state of that the column is horizontal; the beam is vertical and rotated at an angle of 90° compared to the actual conditions. At the position of the end beam, it is arranged to dynamic load jack with a capacity of 500 kN with distance of ± 500 mm placed horizontally parallel to the rigid floor as shown in Figure 2. In addition, a static load jack with a capacity of 1500 kN is also placed horizontally across the end of the column with a constant vertical force of 650 kN during the experiment. A high-strength steel frame that acts as a constrained frame is fastened on rigid floors with high tensile shear bolts on the opposite end. The two ends of the columns are restricted to rotation only and secured by the use of brackets and rollers at the two ends of the column. In addition, each end of the column is fastened to the floor with high strength bolts to prevent movement shift off the plane. The beam-column connection is placed with two displacement measuring (LVDT) to measure development of deformation as shown in Figure 4.

\[
\gamma = \frac{(2D + \delta_1 + \delta_2)(\delta_1 - \delta_2)}{4h_c h_b}
\]

(2)

In which:
- \(D\) is length of diagonal.
- \(\delta\) is variable thickness of LVDT.
- \(a\) - is setting distance of LVDT.
- \(x\) is horizontal strain of beam-column connections.

2.4. Material grades and mechanical properties

The test is performed under cyclic loading. The loading process for all samples consists of two simultaneous processes. At the top of the column, a vertical force of 650kN is applied with a compression ratio of 0.1, at the top of the beam will be controlled by two stages. In the first stage the
force is control phase determining the crack-causing load, in the second stage the displacement is controlled. At the second loading process, displacement control is recommended according to ACI Committee 374 [13]. During this process, dynamic loads were applied under displacement control with a quasi-static frequency of 0.01 Hz. Each loading process consists of 3 cycles with the same displacement and is loaded at the beam end. In the first period the displacement amplitude is equal, then the displacement amplitude of each subsequent step is 1(Δy), 1.4(Δy), 1.75(Δy), 2.2(Δy), 2.75(Δy), 3.5(Δy), 4(Δy), 5(Δy), 6.5(Δy).

\[
Drift = \frac{\Delta_l}{0.5l_b} \times 100
\]  

(3)

In which
\( \Delta_l \) is displacement of beam end
\( l_b \) is length of the beam.

After completing the 12th cycle (1.75%), a control cycle with an amplitude equal to 1/3 of the previous amplitude to avoid loss of stiffness during the loading process [14].

3. Experimental results and evaluation

3.1. Shapes and sample failure

![Figure 5. Failure of the samples at the time of first crack and the maximum load (Drift 2.2%)](image)

The use of UHPSFRC in the beam-column connection zone of samples S2 and S3 is different in length of UHPSFRC zone. The first crack of two samples S2 and S3 appeared in the contiguous position between UHPSFRC and common concrete zone, while the crack of sample S1 appeared at the edge of
column-beam as shown in Figure 14. The comparison of all three samples of beam-column connections at the time of drift of 2.2% shows that there are cracks in all three samples, but in sample S1 showed more cracks in the beam-column connection zone than the S2 and S3 samples. This could be explained by the fact that common concrete has lower shear strength.

Shear stress in beam-column connections is characterized by mechanical properties and stress-strain distribution. The evaluation of shear strength of hinges in this study is based on the nominal value of the shear stress \( V_{ih} \) as calculated in equation (4). The contribution of axial compressive stress in column to shear stresses is also considered. This study implemented the calculation of principal compressive \( p_c \) and tensile stresses \( p_t \) at half of the height of beam-column connection (Fig. 5c) as suggested by Hakuto et al. [15]. Figure 5 shows the force components in beam-column connection during earthquake [16], [17]. In this study, the shape of the beam-column connection is assumed at the inflection points that occur at half of span of the beam and column (Figure 5a). With this assumption \( V_{ib} = V_c \) and \( M_{ib} = M_c \). In addition, in positions the bending moment equal zero it can be determined by assuming the load distributes in vertical and horizontal directions [18].

\[
V_c = \frac{V_{ib} \times L_b}{2H_c} \quad V_{pj} = T_b - T_c \quad V_p = \frac{V_{pj}}{w_j \cdot h_c} \quad f_a = \frac{N_c}{h_c \cdot w_c} \quad P_{ct} = \frac{f_c}{2} \pm \sqrt{\left(\frac{f_c}{2}\right)^2 + \frac{V_{pj}^2}{V_c^2}} \tag{4}
\]

In which: \( p_{t,t} \) is principal tensile and compressive stresses in connection, \( f_a \) is axial compressive stress in column, \( V_{ih} \) shear force in connection, \( T_b \) is tensile force in reinforcement of beam, \( V_c \) is shear force in column, \( V_{pj} \) shear stress, \( V_b \) is applied load to beam, \( L_b \) is span length of beam, \( H_c \) is height of column.

| Sample | Direction | \( V_{ic} \) (kN) | \( V_{pj} \) (MPa) | \( P_c / \sqrt{V_c} \) | \( P_{ct} / f_c \) | \( \mu \) | \( \gamma \) |
|--------|-----------|-----------------|-----------------|----------------|----------------|---|----------------|
| S1     | Compressive | 123.87          | 7.23            | 0.636          | -0.213         | 3.42 | 0.00364        |
|        | Tensile   | -116.60         | -6.80           | 0.677          | -0.177         | 3.8  | -0.00141       |
| S2     | Compressive | 147.20          | 8.59            | 0.562          | -0.119         | 3.41 | 0.00426        |
|        | Tensile   | -142.27         | -8.30           | 0.614          | -0.101         | 3.73 | -0.00172       |
| S3     | Compressive | 154.27          | 9.00            | 0.584          | -0.125         | 3.16 | 0.00643        |
|        | Tensile   | -145.20         | -8.47           | 0.617          | -0.105         | 4.04 | -0.00143       |
The use of UHPSFRC for all test samples showed their better shear strength than sample S1. The improvement is shown in the shear stress characteristics of samples S2 and S3 for S1 control samples by 16% and 20%, respectively, for the case of compressive direction and for the tensile of 18% and 20% (Table 2). This result shows the potential of using UHPSFRC in beam-column connections in frame structures.

3.2. Displacement ductility and evaluation of effectiveness of beam-column connections

The displacement ductility $\mu$ is determined as shown in Figure 6. In which, the maximum displacement $\Delta_u$ is recommended to take 80% of the displacement value at the time of maximum load [19]. The plastic displacement $\Delta_p$ is determined by drawing a line between the origin and a point on the contour curve and the displacement corresponds to 75% of the maximum load. The sample S2 has an equivalent displacement ductility of S1 in both directions. However, the sample S3 does not get the displacement ductility as expected when the load bearing capacity was significantly enhanced but the displacement ductility decreased by 7.6% in the compressive direction, while the tensile direction gave a better improvement of about 6% (Table 2). Thus, it can be seen that the displacement ductility does not increase when the length of the UHPSFRC area is increased from 400 mm of the S2 sample to 675 mm for the S3 sample.

FEMA 273 [20] specifies acceptable limits for shear strain. For reinforced concrete structures, the shear strain at the collapse level "e" is expected to be 0.01 and the strain at the extreme level "d" should not exceed 0.005 (Figure 7). In general, the rules in the design standard Eurocode 8 [1] for beam-column connection of frames are based on internal forces without considering the corresponding strains required to achieve maximum resistance. From Table 2, it can be seen that the both S2 and S3 samples satisfy the shear resistance of connections. The S2 sample has a shear strain lower than the "d" by about 14%, however, the S3 sample is not as expected when the shear strain exceeds the "d" level by 22% but still within the permissible limits of "e" level.

3.3. Principal compressive and tensile stresses

There have been many studies using standardized compression and tensile stress methods to compare the effectiveness of structures [21], [22], [23]. This study assumes a ratio between shear strength and the square root of the concrete compressive strength.
a) Relationship between standardized tensile stress and displacement of S1 sample

b) Relationship between standardized tensile stress and displacement of S2 sample

c) Relationship between standardized tensile stress and displacement of S3 sample

d) The envelope of the principal tensile stress is normalized with displacement

Figure 9. Relationship between standardized tensile stress and displacements

For non-standardized beam-column connections in frame structures, the S2 and S3 samples increase by 20% and 23% respectively in the compressive direction compared to the S1 sample. In contrast, the standardized tensile stresses of the samples are lower than 11.6% and 8.1% in the compressive direction because the strength of UHPSFRC concrete in the beam-column connection zone is much higher than common reinforced concrete (Table 2). This proves that the use of UHPSFRC in the beam-column connection of frame structures has better shear resistance than common reinforced concrete structures.

4. Conclusions
This paper presents a method to enhance shear resistance for reinforced concrete beam-column connections by the application of ultra-high performance fiber reinforced concrete (UHPSFRC). Based on the experimental results, some key conclusions can be shown as follows:

The application of ultra-high performance fiber reinforced concrete (UHPSFRC) helps the beam-column connections have better overall and local behaviour than the control samples even in the case there is no stirrups in the connection zone. The shear strength is increased from 16% to 20% for the case of compressive direction and for the tensile direction is 18% and 20%.
Displacement ductility of S2 sample is similar to that of S1 sample, but S3 sample is decreased. This can be said that the distance of arrangement of UHPSFRC affects significantly the displacement ductility of the structures.

The principal tensile and compressive stresses in non-standardized samples much higher than the control samples, but in contrast, it will be small in standardized samples because of the high compressive strength of UHPSFRC concrete. This proves that the UHPSFRC in the beam-column connections of frame structures has better shear resistance than common reinforced concrete structure.

The beam-column connections in samples S2 and S3 fully meet FEMA 273 [20] criteria. However the result obtained in the S3 sample exceeded the design «d» level. It can be again concluded that the distance of arrangement also affects the shear strain properties of the frame connections.

The application of ultra-high performance concrete materials (UHPSFRC) needs to be further investigated, and more experimental research is needed before recommendations for using in the beam-column connections of frame structures.

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