# Experimental Study on the Structural Ductility of UHPC Beams under Flexure

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**Abstract**

This guide Ultra-high performance concrete shows great potential in the construction industry. However, the structural-level ductility of UHPC members has not been clearly established and is frequently subverted by the crack localization phenomenon. This paper presents an experimental investigation of the structural ductility of a total of twelve UHPC beams tested under flexure. The main variable parameters are the reinforcement ratio, ranging from low to high ratios, and the fibers volumetric ratio, selected as 0%, 1.5%, and 2.5%. The results revealed that 1.5% fiber content and a corresponding reinforcement ratio between 1.2 % - 4.4% are generally adequate for generating sufficient ductility on a structural level, and further increasing the fiber content has a minimal enhancement to the ductility. Moreover, adding fibers is not only necessary to improve the ductility from the tension side, but also from the compression side as the fibers impose a slow and gradual crush of UHPC, thereby improving the ductility in the post-peak branch.

**Keywords:** ultra-high performance concrete; UHPC; structural ductility; flexure.

## 1. Introduction

Ultrahigh-performance concrete (UHPC) is one of the up-to-the-minute construction materials invented in recent times. UHPC is exhibit extraordinary mechanical properties, including high compressive strength ( usually more than 150MPa), sustained post-cracking tensile strength, and remarkable durability (Russel and Graybeal 2013). UHPC has gathered worldwide interest for its high potential in the construction industry. Despite that, its application in full and large structural components remains constrained by several factors, one of which is the lack of consistent and practical design models. In addition, the ductility of UHPC at a structural level is still an unresolved issue and is usually compromised by the crack localization phenomenon.

Considerable research efforts have been devoted to exploring the ductility of UHPC at a structural level. It has been shown that reinforced members made of UHPC exhibit distinctive cracking patterns and failure modes, and thus the ductility criteria of reinforced UHPC are unique and not only governed by the reinforcement, as in normal concrete but also by the fiber contents and properties. It is established that the fundamental objective of adding fibers to concrete is restraining the cracks through the bridging action and enhancing the post-cracking resistance. However, as the strain of UHPC (or crack width) reaches a certain threshold, typically recognized as crack localization, the fiber bridging action begins to diminish and quickly fade away. Baby et al. (2014) reported that, in strain-hardening UHPC, the coupled contribution of reinforcement and fibers is more efficient if the crack localization strain capacity of the UHPC at a structural level is much larger than the yielding strain of the reinforcing steel. Yoo and Yoon (2015) reported that including 2% steel fibers significantly increased the capacity of UHPC beams, but resulted in a decline in the ductility when compared with typical specimens with 0% fiber content, which was caused by the localized deformation of the reinforcement locally deformed at a dominant localized crack. Shao and Billington (2019) highlighted that the ductility of UHPC is governed by the strain-hardening capacity of the reinforcing rebar, which is required to compensate for the decline in fiber bridging contribution to the overall load-carrying capacity. That is, the ductility of reinforced UHPC is affected by the fiber content represented by the tensile resistance of UHPC, reinforcement ratio, and strain-hardening capacity of the reinforcement. This remark was further supported by the experimental investigation carried out by Qiu et al. (2022).

Further studies are still required to establish a clear understanding of the key factors affecting the ductility of UHPC beams and assist in accomplishing a ductile design. This paper is devised to further investigate the structural ductility of reinforced UHPC and presents an experimental investigation on the structural ductility of a total of twelve UHPC beams tested under flexure. The main variable parameters are the reinforcement ratio, ranging from low to high ratios, and the fibers volumetric ratio, selected as 0%, 1.5%, and 2.5%.

## 2. Experimental Program

### 2.1. UHPC Mixture Design

The UHPC mixture consisted of proprietary cementitious UHPC powder (produced by SuBoTe CO., LTD), water, superplasticizer, and high-strength steel fibers. Smooth straight steel fibers were used in the mixture and were randomly distributed during casting. The volumetric ratio of the steel fibers was taken as an investigated variable parameter. The UHPC mixture proportions are listed in Table 1, and the properties of the used steel fibers are listed in Table 2.

**Table 1. UHPC mixture proportions.**

| Component | UHPC powder | Water | Superplasticizer | Steel fibers |
|---|---|---|---|---|
| (kg/m$^3$) | 2232 | 192.4 | 15.38 | Variable |

**Table 2. Properties of steel fibers.**

| Diameter (mm) | Length (mm) | Aspect ratio (mm) | Tensile strength (MPa) | Elastic modulus (GPa) | Density (kg/m$^3$) |
|---|---|---|---|---|---|
| 0.2 | 13 | 65 | 2600 | 205 | 7840 |

### 2.2. Test Specimens

The test program included a total of twelve specimens. The cross-section of the beam was 150 mm wide, and 250 mm high, and the total length of the beam was 2700 mm, as shown in Figure 1. The specimens were sorted into three groups labeled in accordance with the selected fiber volumetric ratio, denoted as UN, U1.5, and U2.5, referring to 0%, 1.5%, and 2.5% fiber content, respectively. Each group includes four beams with four different reinforcement ratios ranging from a low to high ratio, selected as 1.26%, 2.44%, 4.41%, and 7.07%. A dense transverse reinforcement was adopted to prevent shear failure. A summary of the test specimens and the considered parameters is given in Table 3.

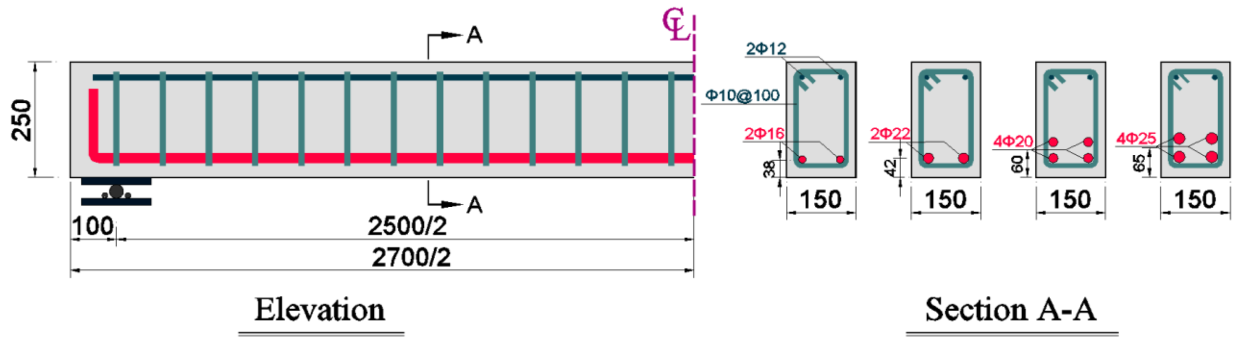



**Figure 1. Geometry and reinforcement details of the test specimen**

**Table 3. Summary of the test specimens**

| Group | Specimen No. | Fiber volumetric ratio (%) | Longitudinal reinforcement | Reinforcement ratio |
|---|---|---|---|---|
| UN | UN-1 | 0 | 2 $\phi$14 | 1.26 |
| | UN -2 | | 2 $\phi$20 | 2.44 |
| | UN -4 | | 4 $\phi$20 | 4.41 |
| | UN -7 | | 4 $\phi$25 | 7.07 |
| U1.5 | U1.5-1 | 1.5 | 2 $\phi$14 | 1.26 |
| | U1.5-2 | | 2 $\phi$20 | 2.44 |
| | U1.5-4 | | 4 $\phi$20 | 4.41 |
| | U1.5-7 | | 4 $\phi$25 | 7.07 |
| U2.5 | U2.5-1 | 2.5 | 2 $\phi$14 | 1.26 |
| | U2.5-2 | | 2 $\phi$20 | 2.44 |
| | U2.5-4 | | 4 $\phi$20 | 4.41 |
| | U2.5-7 | | 4 $\phi$25 | 7.07 |

## 2.3. Loading and Instrumentation

The beams were loaded in a four-point bending scheme, as illustrated in Figure 2. The center-to-center span was 2500 mm, the shear span was 1000 m, and the pure bending region was 500 mm. LVDTs were used for measuring the displacement at seven stations along the span and for measuring the nominal strain at the top and bottom of the section at mid-span. Strain gauges were attached to the reinforcement and the concrete cover at the mid-span for collecting the strain data, see Figure 2.

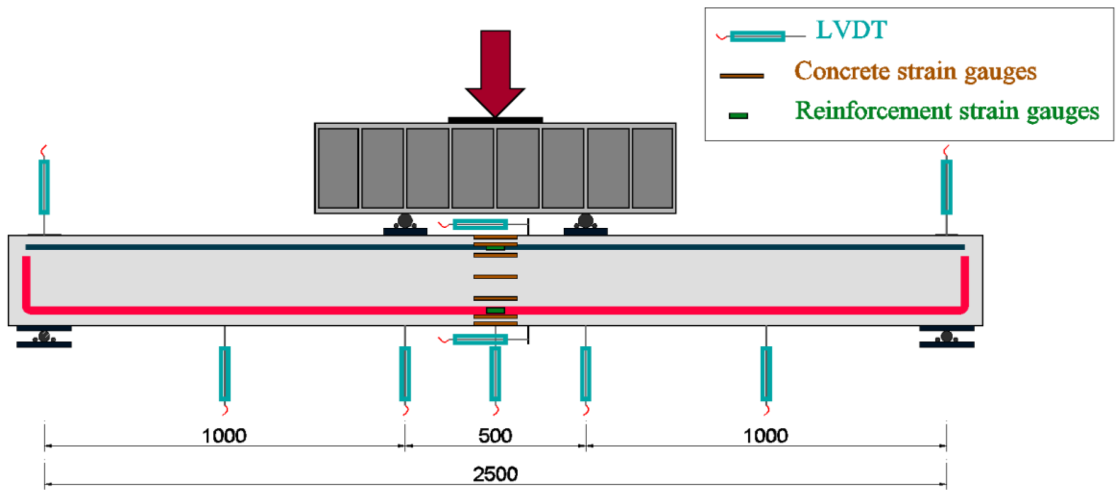
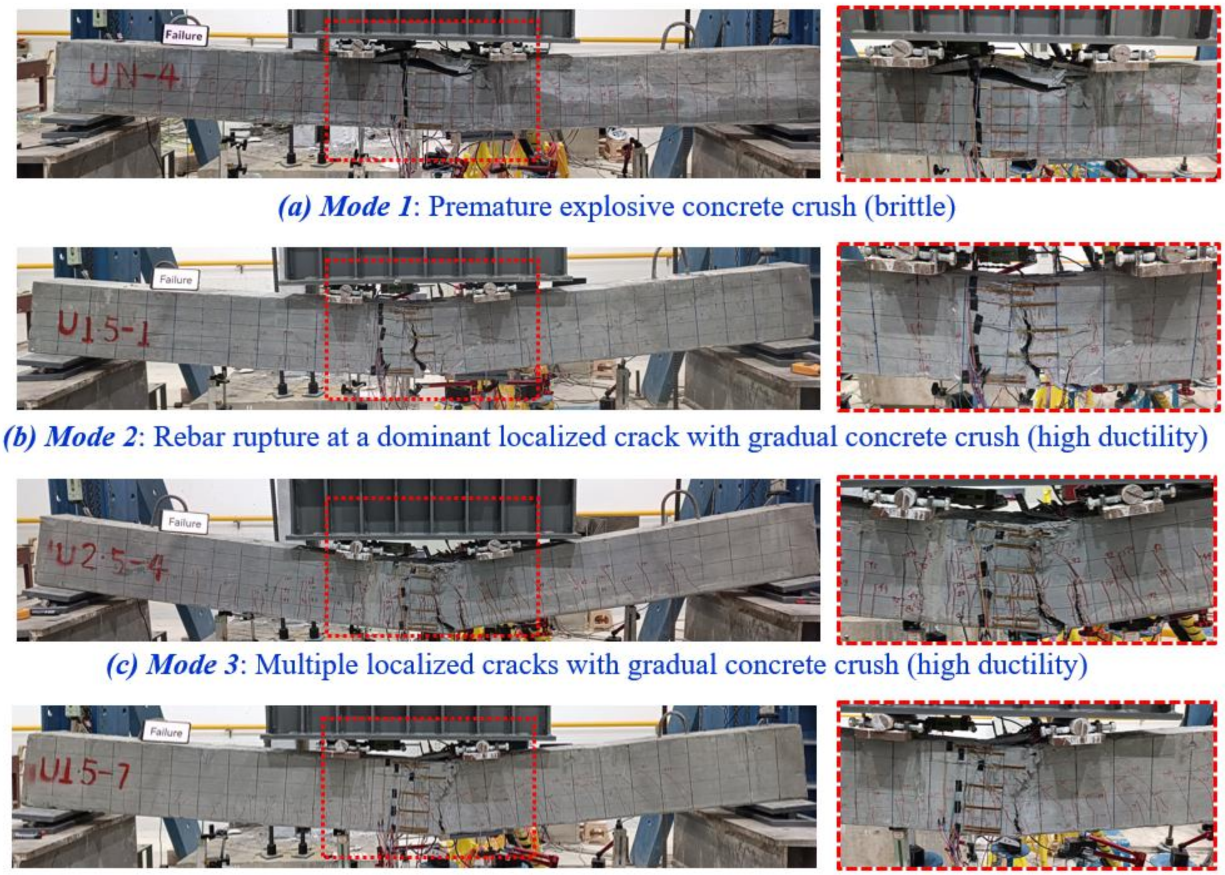



**Figure 2. Loading and instrumentation**

## 3. Results and Discussions

### 3.1. Cracking and Failure Modes

The observed cracking and failure patterns are categorized into four modes, as illustrated in Figure 3. For the specimens with a UHPC mixture without fibers (UN), the cracking pattern was demonstrated by the formation of uniformly-spaced cracks at early stages followed by a sudden explosive concrete crush, in which the compression zone was detached upward from the section, this mode is denoted by Mode 1, see Figure 3 (a). Mode 1 was dominant in all specimens UN group regardless of the steel reinforcement ratio. This explosive crush mode is attributed to the absence of fibers that have a bridging action during the formation of the splitting cracks under compression. In Mode 2, the specimens demonstrated a cracking pattern featured by few localized cracks, of which a dominant crack proceeded to widen along with gradual concrete crush, as illustrated in Figure 3 (b). This mode appeared in specimens with a relatively low reinforcement ratio (1.26%) in both groups with 1.5% fiber content and 2.5% fiber content, indicating that increasing the fiber content did not significantly impact the cracking and failure modes. The third mode, Mode 3, was featured by multiple localized cracks with relatively large crack widths along with gradual concrete crush, see Figure 3 (c). This mode appeared in specimens with relatively middle to high reinforcement ratios, 2.44%, and 4.41%, in both groups U1.5 and U2.5. In this mode, the adequate reinforcement ratio was the key factor for enforcing a slow and uniform crack widening accompanied by gradual concrete crush, analogous to tension-controlled sections. Finally, in Mode 4, the specimens exhibited a failure mode initiated and governed by concrete crush at early loading stages accompanied by some localized cracks, as shown in Figure 3 (d). This mode occurred in specimens with a relatively high reinforcement ratio, 7.07%, with a fiber content of 1.5% and 2.5%. This mode can be sorted into a transition zone between tension-controlled and compression-controlled sections. A summary of the failure modes observed in the tested specimens is given in Table 4.




***(a) Mode 1***: Premature explosive concrete crush (brittle)

***(b) Mode 2***: Rebar rupture at a dominant localized crack with gradual concrete crush (high ductility)

***(c) Mode 3***: Multiple localized cracks with gradual concrete crush (high ductility)

***(d) Mode 4***: Concrete crush at early stages (limited ductility)

**Figure 3. Typical failure modes**

**Table 4. Summary of failure modes**

| Failure mode | Specimen No. | Description |
|---|---|---|
| Mode 1 | UN-1, UN-2, UN-4, UN-7 | The failure mode is governed by premature explosive brittle concrete crush, attributed to the absence of fibers |
| Mode 2 | U1.5-1, U2.5-1 | The failure is governed by reinforcement rupture at a dominant crack that continues to widen out of few localized cracks, i.e., multiple localized cracks but with one dominant crack. This mode is accompanied by gradual concrete crush. |
| Mode 3 | U1.5-2, U2.5-2, U1.5-4, U2.5-4 | The failure mode is governed by multiple localized cracks with large widths along with gradual concrete crush. |
| Mode 4 | U1.5-7, U2.5-7 | The failure mode is governed by concrete crush at early stages, accompanied by a dominant or few localized cracks. |

## 3.2. Load-displacement Response

The load-displacement curves for each group are presented in Figure 4. It can be seen that increasing the reinforcement ratio significantly increases the load capacity in all specimens, which is consistent with most of the observations reported in the literature. All the specimens without fibers (UN group), regardless of the reinforcement ratio, showed a sudden drop in the load-displacement response due to the explosive concrete crush, see Figure 4 (a). On the other hand, when fibers were included in the mixture as in groups U1.5 and U2.5, a longer response path was obtained, see Figure 4 (a) and (b). In these two groups, the influence of increasing the reinforcement ratio on the ductility was more noticeable. With a low reinforcement ratio, U1.5-1 and U2.5-1, the response path was relatively long, exhibiting high ductility. With a reinforcement ratio between 2.44% and 4.41%, as in U1.5-2, U1.5-4, U2.5-2, and U2.5-4, the response was very long and a high ductility was obtained. Further increasing the reinforcement ratio takes the response towards a path analogous to that of a transition zone section in normal concrete, which is featured by concrete crush at early to middle loading stages.

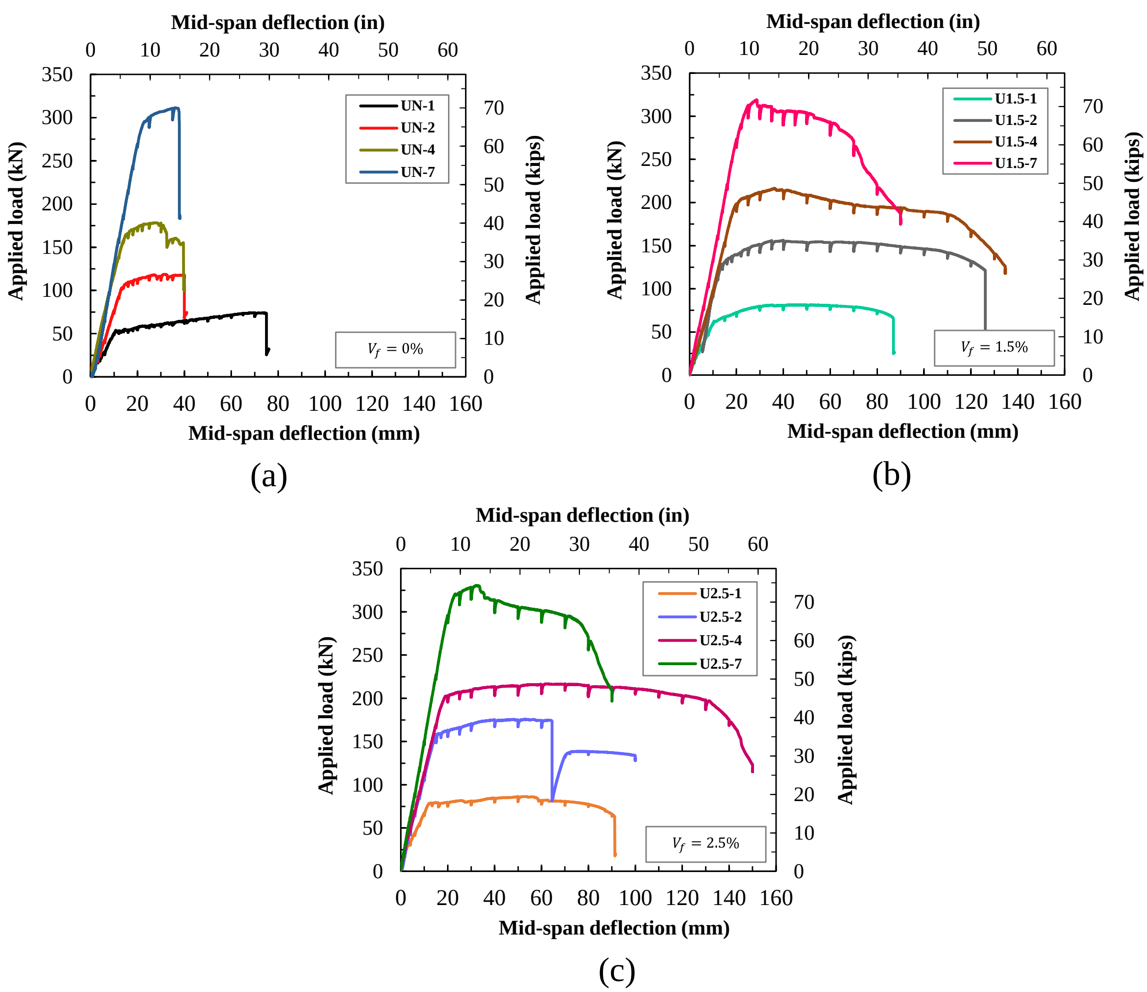



**Figure 4. Load-displacement curves**

### 3.3. Ductility

The ductility is assessed using the deflection ductility index $\mu_u$, computed by

$$\mu_u = \frac{\Delta_u}{\Delta_y} \tag{1}$$

where $\Delta_y$ and $\Delta_u$ are the deflections corresponding to the yielding, and ultimate states, respectively. $\Delta_u$ is taken as the deflection corresponding to 80 % of the peak load on the descending branch in the specimen that showed a long descending branch or as the last deflection point in the specimen that failed prior to reaching 80 % of the peak load.

The results of the ductility index of the tested specimens are presented in Figure 5. It can be noticed that increasing the reinforcement ratio results in a decrease in the ductility in all fiber content conditions, as shown in Figure 5 (a). All specimens without fibers (UN group) showed poor ductility, except for the specimen with a low reinforcement ratio of 1.26%. Increasing the fiber content from 0% to 1.5 % significantly increases the ductility, as shown in Figure 5 (b). Increasing the fiber content from 1.5% to 2.5% minimally increases the ductility. Typically, adequate ductility can be achieved with a fiber content of 1.5% accompanied by a reinforcement between of 1.26%-4.41%.

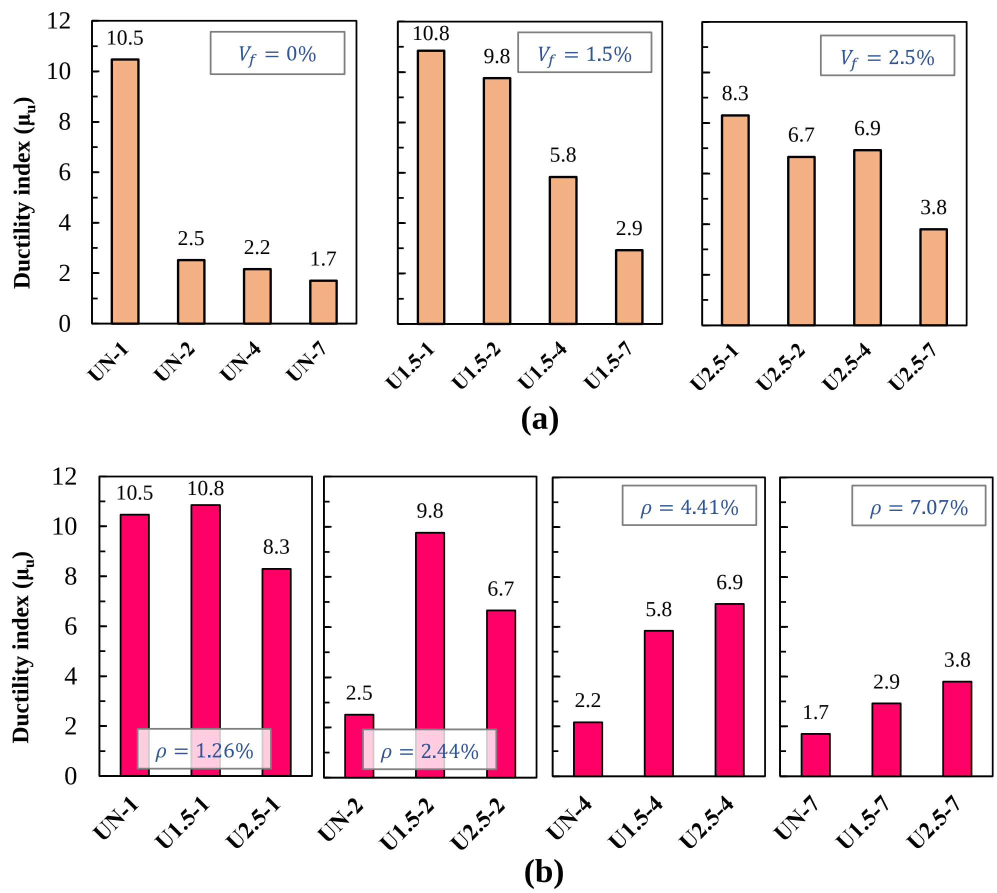



**Figure 4. Deflection ductility index for the tested specimens with: (a) different reinforcement ratios, and (b) different fiber contents**

## 4. Conclusion

This paper presented an experimental investigation of the structural ductility of reinforced UHPC beams under the impact of two main parameters, the fiber content and reinforcement ratio. It can be concluded that 1.5% fiber content and a corresponding reinforcement ratio between 1.2 % - 4.4% are generally adequate for generating sufficient structural ductility in UHPC members, and further increasing the fiber content provides a minimal enhancement to the ductility in general and the capacity in beams with high reinforcement ratios. Besides, adding fibers is not only essential for improving the ductility from the tension perspective, but also from the compression perspective as the fibers restrain the splitting and micro-cracks in the compression zone and impose a slow and gradual crush of UHPC, which also contributes to the overall ductility.

## 5. References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