Flexural capacity of singly reinforced beam with 150 MPa ultra-high-strength concrete

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In this paper, we have studied the 150 MPa ultra-high-strength concrete (UHSC). RC beam is reinforced by SD400 and SD500 bars to evaluate on range of maximum tensile steel ratio which have reasonable ductility capacities and flexural behaviors of UHSC through the flexural test. The reinforced ultra-high-strength-concrete beam subjected to flexural moment behaves more brittleness than the reinforced moderate strength concrete beam with equal reinforcement ratio \((\rho/\rho_b, \rho_b=\text{balanced steel ratio})\). In this study, 10 singly reinforced rectangular beam specimens using 150 MPa concrete compressive strength are tested to evaluate on flexural behavior. The ductility capacity of UHSC flexural member without compression reinforcements significantly decrease. Displacement ductility index indicates about 1.3~2.56 on 150 MPa UHSC. To obtain the minimum ductility ratio with above 3.0 for double reinforced beam and above 2.0 for singly reinforced beam, limit strain shall be set so that the net tensile strain of outermost tensile steel may be above 0.006 in excess of 0.005 and the tensile steel ratio is required to be 0.55 \(\rho_b\) or less.

**Keywords**: Ultra-high-strength-concrete, Maximum tensile steel ratio, Ductility, Flexural behavior

High-strength concrete is a safe and economical material that maximizes the advantages of concrete when used as a compressive member. However, high-strength concrete shows more brittle than ordinary strength concrete, and thus ductility of structures decreases. Overall structural safety of structures might be diminished, if there are no additional works to supplement the characteristics that cause brittle failure. Also, since wider cross-section more than certain level of size is required to meet the requirement of serviceability like crack or deflection by controlling flexural bending stiffness of members, use of ordinary strength concrete is generally used for designing reinforced concrete for bending member like beam, even if high-strength concrete is used for column. However, if the strength of bending member does not increase while the strength of concrete for compressive member increases gradually, the safety of structure may be decreased due to the relative stiffness difference between column and beam. Therefore, if the strength of bending member also increases when the strength of concrete of compressive member increases, not only the durability of structure but also the relative stiffness of horizontal and vertical members that are required in Korea and in other countries can be used effectively.

On the other hand, as the construction of super-high structures and long-span structures increases all over the world, strength and stiffness of structures are being improved by applying ultra-high-strength concrete, and in particular, the production of CO\textsubscript{2} is reduced as the durability of structures are enhanced, and finally it contributes to design method to emit low carbon during life cycle of structure. With such trends, demands to use 100 MPa or ultra-high-strength concrete more than that are anticipated to spread out and, thus studies that acquire the ductility of structure are widely demanded for structures designed by reinforced concrete\textsuperscript{1-3}.

In ACI 318-024 building code and KCI 2007 Standard 5, the design method to determine the maximum steel ratio of tensile steel are newly introduced for bending member. According to the previous code, the ratio of maximum tension steel shall be limited to 75% or less of balanced steel ratio \((\rho_b)\) because of the need to restrict excessive use of tension steel, and to prevent bending member from brittle fracture and then to induce ductile fracture. However, the revised code stipulates that with the
cross-section stress by the behavior of bending member divided into compression controlled cross-section, transition zone cross-section and tension controlled cross-section with reference to the outer net tensile strain of tensile reinforced concrete, the tension controlled cross-section that can secure ductile behavior shall be defined as the value measured when the net tensile strain of outermost tensile reinforced concrete is 0.005 or above, and the net tensile strain of bending member on which free stress is not applied shall be limited to minimum allowable strain of 0.004 or above. However, the revised code divides the cross-section controlled by the compression, the tension, and transition zone between two zones. The cross-section controlled by the tension to have the ductile behavior is defined as the net tensile strain of the outer tensile steel is more than 0.005 and is limited that the net tensile strain of bending member without pressing is more than 0.004 of the minimum allowable strain (Fig. 1).

If the amount of tensile steel ($A_s$) is greater than the amount of steel ($A_{sb}$) which leads to balanced strain condition, the depth of compressive stress block ($\alpha$) increases. Therefore, when the strain of concrete in compression block reaches ultimate strain ($\varepsilon_u = 0.003$), the net tensile strain ($\varepsilon_s$) of outermost tensile steel or tendon will not reach the compression-controlled strain limit ($\varepsilon_c$). Such bending member, when excessive loading is applied, leads to sudden fracture of compressive concrete without any notice such as deflection shown externally. On the contrary, if the amount of tensile steel ($A_s$) is less than the amount of steel in balanced condition ($A_{sb}$), the depth of compressive stress block ($\alpha$) decreases. Therefore, the net tensile strain ($\varepsilon_s$) of outermost tensile steel or tendon will increase far beyond 0.004, the limit of minimum allowable strain, which is the value when SD 400 is used (0.005 for SD 500), before the compressive strain of concrete ($\varepsilon_c$) in compression block reaches ultimate strain ($\varepsilon_u = 0.003$). In other words, when excessive loading is applied, tensile steel yields before compressive concrete are fractured, and thus precaution is delivered before the fracture. Therefore, by providing a sufficient time for countermeasure before serious problem occurs, ductile fracture may be deemed desirable as a form of fracture.

Therefore, to guarantee such form of ductile fracture, $0.75 \rho_b$, the ratio for balanced steel ratio, $(\rho/\rho_b)$ was set to the maximum allowable steel ratio in earlier designing code, and has been applied to the limit of tensile strain implicitly. But, ACI 318-02 and KCI 2007 provide that “the net tensile strain ($\varepsilon_s$) at nominal strength shall be the minimum allowable steel ratio by the yield strength based on design code of rebar and the rate of the steel ratio by balanced steel ratio may be shown in Table 1. Table 2 shows the strain limit of each control cross-section and the tension controlled limit cross-section of bending member by the design based yield strength of steel as steel ratios the form of past

![Fig. 1 — Limits of the tension-controlled strain](image-url)
designing standard, indicating as the rate against 
balance steel ratio. Table 2 also explains the strain 
limit of each controlled section based on the yield 
strength of steel and shows the steel ratio of tension 
controlled cross-section for bending member as a 
form of past design code.

This study intends to determine if the newly revised 
code can be applied to bending member using ultra-
high-strength concrete of which compressive strength 
is 150 MPa. Also, in case of concrete beam subjected 
to bending, the distribution of compressive stress 
occuring on cross-section shows parabola curve 
similar with the shape of stress-strain curve obtained 
by concrete specimen experiment, and in ACI and 
Korean code, presently, bending strength is calculated 
by simplifying it as a rectangular shape. However, 
stress-strain curve of ultra-high-strength concrete 
shows triangular shape which remains nearly linear up 
to maximum stress, and thus it is necessary to 
examine if bending strength of ultra-high-strength 
concrete beam can be calculated by assuming 
rectangular stress block. Therefore, this study intends 
to evaluate the range of maximum tensile steel ratio 
required to obtain ductile behavior of bending 
member using ultra-high-strength concrete through 
bending experiment on RC singly reinforced beams 
which are reinforced with 150 MPa ultra-high-

### Table 1 — The minimum allowable strain and the relevant steel 
ratio of the flexural structure

<table>
<thead>
<tr>
<th>Yield strength of</th>
<th>Bending member tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>rebar designing</td>
<td>Minimum allowable strain</td>
</tr>
<tr>
<td>standard</td>
<td></td>
</tr>
<tr>
<td>300 MPa</td>
<td>0.004</td>
</tr>
<tr>
<td>350 MPa</td>
<td>0.004</td>
</tr>
<tr>
<td>400 MPa</td>
<td>0.004</td>
</tr>
<tr>
<td>500 MPa</td>
<td>0.005 $(2\varepsilon_y)$</td>
</tr>
</tbody>
</table>

### Experimental Procedure

#### Concrete mix design and used materials

The cement used in the manufacturing of ultra-
high-strength concrete was 4-component free mix 
cement, the used coarse aggregates were those which 
size in maximum is 13 mm, and fine aggregates were 
mixture of sea sands and crushed sands. As for 
chemical compounds, high performance PC 
compounds were used to reduce the effects on 
strength development and specimen placement. The 
mixed ratios of 150 MPa ultra-high-strength concrete 
are shown in Table 3.

#### Mechanical properties of concrete

In this experiment, specimen was produced by 
using $\Phi$100×200 mm mold of cylinder type. 
Compressive strength test of ultra-high-strength 
concrete was done in accordance with KS F 2405, the 
results were shown in Table 4. Though the stress-
strain curve of ultra-high-strength concrete increases 
as a linear shape, accurate test results for the softening 
region after inflection point could not be obtained due 
to sudden brittle fracture.

| Table 3 — Mix of the ultra high-strength concrete in batch plant(B/P) |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Class                     | W/B (%) | S/a (%) | Unit weight (kg/m$^3$) | Total weight (kg/m$^3$) | Slump flow (mm) | Air (%) |
| Specification mix         | 12.6     | 30      | 1154 145 287 72 837 | 34.6 2495 | -       | -      |
| Field mix                 | 12.6     | 30      | 1154 131 306 77 827 | 34.6 2495 | 700/720 | 2.0    |
The tensile strengths of steel reinforcement were measured in accordance to KS B 0802, and were shown in Table 5. Results of steel reinforcement after tension test shows that the yield strengths of steel were at the range of 477 ~ 610 MPa, and tensile strength were 627 ~ 739 MPa. Steel were shown to be yielding when the yield strain approached to the range of 0.0025 ~ 0.0033.

Specimen plan

The main points that affect the ductile behavior of bending member in reinforced concrete include compressive strength of concrete, tensile steel ratio and the distance between shear rebar, but in this study, 10 cases were considered, which were \( \rho = 0.45, 0.55, 0.625, 0.714, 0.75 \) \( \rho_b \) for specimens using SD 400 tensile steel and \( \rho = 0.45, 0.55, 0.595, 0.688, 0.75 \) \( \rho_b \) for specimens using SD 500 tensile steel by adopting tensile steel ratio as a main variable, and ultra-high-strength concrete of 150 MPa compressive strength was applied to total 10 bending specimens which were singly reinforced beams.

The specimens were designed based on the design method of singly reinforced beam specified in ACI. The tensile steel applied in each specimen was D10, D16, D22, D25 and D29 reinforcement steels, and were reinforced doubly by combining each reinforcement with the tensile steel ratio required by each specimen.

Each specimen was designed to be 220×250 mm in cross-section and 3,200 mm in span so that the amount and distance of reinforcement shall be meet tension reinforcement ratio by each parameter and the concrete compressive strength was 150 MPa. All specimens were loaded on the 4 points to induce net bending moment.

For net bending region, in singly reinforced beam, only tensile steel was arranged without compressive reinforcement or shear reinforcement. In order to prevent shear failure and crack of specimen in the zone from both supports to loading points (specimen that has maximum steel reinforcement ratio: \( a/d=5.5 \), specimen that has minimum steel reinforcement: \( a/d=3 \) or above), sufficient shear reinforcement was done. The details on specimen are shown in Table 6 and Fig. 2.

Experiment method

In the experiment, both ends of specimen were installed in simple supported condition as shown in Figs 2 and 3. Specimen was divided into 3 parts and loading was constantly applied to the 4 points of specimen. To measure the deflection, 3 LVDT were installed at the center of span and at both loaded points, and LVDT was installed at the point which neutral axis exists considering deflection at bottom by specimen rotation. Also, to measure the strain of reinforcement, strain gauges were attached to the center of outermost tensile steel and the top reinforcement of the same point so that the trend of the strain at the both top and bottom may be analyzed in loading point. In addition, to measure the strain of concrete, 3 concrete gauges were attached from the bottom of compression block to the center of cross-section. Loading was applied by load-controlled method which increases constantly up to 1/3 of final fracture load, and thereafter, loading was applied by displacement-controlled method while the deflection of LVDT installed at center was observed. Test instruments were Actuator (2,000 kN), Data Logger (TDS 302), LVDT and Load Cell (1,000 kN) etc.
Results and Discussion
The results about measurement of estimated maximum load by each specimen, load by experiment stages and deflection by the stages were shown in Table 7.

Crack occurrence and failure
This experiment shows a pure bending by 4 points load, the central part of the specimen selected as a pure bending zone is a zone reinforced only with tensile steel without compressive reinforcement or

<table>
<thead>
<tr>
<th>Specimens</th>
<th>$f_{ck}$ (MPa)</th>
<th>$f_t$ (MPa)</th>
<th>Arrangement of steel</th>
<th>$\rho_b$</th>
<th>$\rho$</th>
<th>$\rho_t$</th>
<th>$\varepsilon_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-BH4-a</td>
<td>150</td>
<td>1-D16 + 4-D25</td>
<td>0.45 (0.452*)</td>
<td>0.056 (0.056)</td>
<td>0.0080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-BH4-b</td>
<td>500</td>
<td>1-D16 + 5-D25</td>
<td>0.55 (0.555)</td>
<td>0.068 (0.069)</td>
<td>0.0060</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-BH4-c</td>
<td>1200</td>
<td>3-D22 + 3-D29</td>
<td>0.1243</td>
<td>0.714 (0.710)</td>
<td>0.089 (0.088)</td>
<td>0.0040</td>
<td></td>
</tr>
<tr>
<td>15-BH4-d</td>
<td>400</td>
<td>1-D19 + 5-D29</td>
<td></td>
<td>0.75 (0.755)</td>
<td>0.093 (0.094)</td>
<td>0.0036</td>
<td></td>
</tr>
<tr>
<td>15-BH5-a</td>
<td>500</td>
<td>3-D22 + 2-D25</td>
<td></td>
<td>0.45 (0.462)</td>
<td>0.041 (0.042)</td>
<td>0.0078</td>
<td></td>
</tr>
<tr>
<td>15-BH5-b</td>
<td>150</td>
<td>5-D22</td>
<td></td>
<td>0.55 (0.541)</td>
<td>0.049 (0.049)</td>
<td>0.0062</td>
<td></td>
</tr>
<tr>
<td>15-BH5-c</td>
<td>200</td>
<td>3-D22 + 2-D25</td>
<td></td>
<td>0.688 (0.683)</td>
<td>0.062 (0.062)</td>
<td>0.0043</td>
<td></td>
</tr>
<tr>
<td>15-BH5-d</td>
<td>300</td>
<td>5-D22 + 1-D25</td>
<td></td>
<td>0.75 (0.754)</td>
<td>0.068 (0.068)</td>
<td>0.0036</td>
<td></td>
</tr>
</tbody>
</table>

15: Concrete compressive strength ($f_{ck}$ = 150 MPa)
$\rho_b$: Balanced reinforcement ratio, $\rho$: Tension steel ratio
*$*$ : Tension steel ratio by actual reinforcement amount
BH4, 5: Steel tensile strength ($f_t$: 400, 500 MPa)
$\rho_t$: steel ratio of tension-controlled strain limit state (0.005)
a, b, c, d, e: variables of tension steel ratio
$\varepsilon_t$: Net tensile strain

Fig. 2 — Conditions of the steel arrangement and set up for specimen
shear reinforcement. Fig. 4 shows the distribution of crack occurrence and final fracture of each specimen depending on test variables.

In all the specimens, initial bending crack was occurred at the center of specimen when load was applied from 26 to 43 kN (5 to 10% of estimated maximum load), and cracks were occurred at 70 to 80 mm distance from center to end of specimen. It was found that though difference exists depending on specimen by test variables, tensile steel yielded and the speed of crack propagation grew faster gradually when 50 to 70% of maximum load was applied. Also, after member yield, the crack that developed from tension side progressed gradually, but as the crack of compressive side propagated significantly. When it reached to the maximum load, the load decreased gradually until about 90% of maximum load, and parting of compressive side concrete started. And it followed by sudden decrease of load and brittle bending fracture was occurred by crushing of compressive side concrete. Figure 5 shows the partial bonded crack that occurred at the top reinforcement of Fig. 4 shows the distribution of crack occurrence and final fracture of each specimen depending on test variables.

Table 7 — Test results for each specimen

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Estimated maximum load (kN)</th>
<th>Load (kN)</th>
<th>Deflection (mm)</th>
<th>Nominal moment (M_n: kN·mm)</th>
<th>Displacement ductility index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P_cr</td>
<td>P_y</td>
<td>P_max</td>
<td>P-final</td>
<td>Δ_cr</td>
</tr>
<tr>
<td>15-BH4-a</td>
<td>293.8</td>
<td>25.5</td>
<td>234.2</td>
<td>360.3</td>
<td>315.8</td>
</tr>
<tr>
<td>15-BH4-b</td>
<td>351.7</td>
<td>33.4</td>
<td>305.9</td>
<td>444.2</td>
<td>391.4</td>
</tr>
<tr>
<td>15-BH4-c</td>
<td>393.0</td>
<td>42.2</td>
<td>348.7</td>
<td>495.5</td>
<td>442.8</td>
</tr>
<tr>
<td>15-BH4-d</td>
<td>440.3</td>
<td>35.3</td>
<td>367.1</td>
<td>451.3</td>
<td>401.5</td>
</tr>
<tr>
<td>15-BH4-e</td>
<td>458.4</td>
<td>33.4</td>
<td>414.6</td>
<td>438.1</td>
<td>422.1</td>
</tr>
<tr>
<td>15-BH5-a</td>
<td>269.7</td>
<td>43.2</td>
<td>269.5</td>
<td>417.0</td>
<td>374.5</td>
</tr>
<tr>
<td>15-BH5-b</td>
<td>323.0</td>
<td>33.4</td>
<td>316.1</td>
<td>461.9</td>
<td>397.8</td>
</tr>
<tr>
<td>15-BH5-c</td>
<td>346.5</td>
<td>35.3</td>
<td>369.8</td>
<td>451.3</td>
<td>416.4</td>
</tr>
<tr>
<td>15-BH5-d</td>
<td>393.2</td>
<td>26.5</td>
<td>316.1</td>
<td>404.1</td>
<td>373.1</td>
</tr>
<tr>
<td>15-BH5-e</td>
<td>423.3</td>
<td>42.2</td>
<td>368.7</td>
<td>522.1</td>
<td>446.1</td>
</tr>
</tbody>
</table>

Δ_cr: deflection at P_cr, mm
Δ_y: deflection at P_y, mm
Δ_max: deflection corresponding to 80% of it after maximum load
Δ_pf: deflection at P_final, mm
M_test: test value of ultimate moment, kN·mm
M_ACI: moment calculate value of ACI standard, kN·mm
µ_Δ_80: displacement ductility index of Δ_80 standard
µ_Δ_pf: displacement ductility index of Δ_pf standard

Fig. 3 — Set-up of specimen
Fig. 4 — Final failure mode and the cracks occurring state for each specimens
doubly reinforced tensile steel when compressive side concrete is crushed and such crack propagated toward tension side. The lower the tensile steel reinforcement ratio shows the less frequent crushing, and the number of cracks was occurred less, and the more hair cracks of 0.1 to 0.2 mm were shown.

**Load-deflection curve**

The load-deflection curves by each specimen were shown by the series in Figs 6 and 7. As shown in Figs 6 and 7, all the specimens showed almost linear load-deflection relations from initial load to maximum load, and that indicates that the behavior up to maximum load is very elastic just like the stress-strain curve obtained in the compressive strength test of cylinder specimen due to the elastic nature with 150 MPa concrete strength. In addition, compared with the initial rigidity of each specimen, the rest of specimens excluding the specimen with 0.45 $\rho_b$ showed very similar rigidity.

In comparison of the maximum load of each specimen, the capacity of specimen with 0.75 $\rho_b$ of tensile steel ratio has highest load, and just like in Fig. 8, the difference between the nominal moment value obtained by calculation and experiment value was shown to decrease with increase of reinforcement ratio. However, in case of reinforcement ratio of 0.625 $\rho_b$ or above, calculated value and experiment value show no difference, and the increase of experiment value was determined not high due to over reinforcement of tensile steel and the brittle fracture of compressive concrete. In addition, as load decreased after maximum load, deflection increased, but until about 90% of maximum load, load decreased gradually and thereafter, the specimen showed brittle behavior reaching final fracture by the sudden crushing of compressive side concrete. This indicates that consideration needs be taken to prevent sudden brittle fracture of compressive concrete after maximum load when ultra-high-strength concrete was designed for bending, and thus proper reinforcement was done through constraining of compressive steel and shear steel. Rashid also proposed that at 100 MPa of concrete strength, tensile steel ratio should be limited to 0.4 $\rho_b$ or less, and since lateral buckling may occur even at 200 mm interval of shear reinforcement in pure bending zone, it is determined that shear reinforcement interval for it also should be considered delicately.

**Ductility index**

In reinforced concrete, ductility refers to the capacity of structure or member to maintain considerable non-elastic deformation until collapse without experiencing sudden fracture by applied load. In general, $\Delta_{80}$ is the “final displacement” of member equivalent to 80% of maximum load coming.
after maximum load along the down-coming part of load-displacement curve. However, some researchers at times consider the area up to the load equivalent to the load at which specimen yields along the down-coming part of load-displacement curve µ₅ as “final displacement”. Nevertheless, since the concept of ductility is related to the capacity to resist non-elastic deformation with no practical decrease of load in carrying load, the definition of ductility based on Δ₈₀ is judged as logical and practical approach. As shown in Fig. 9, member is regarded as having yielded in case the strain of tensile steel exceeds yield strain (εᵧ = 0.002), and thus the deflection amount at this moment is calculated as yield displacement (Δᵧ). In case of ultra-high-strength concrete of 100 MPa or above, sudden fracture tends to occur after maximum load, and thus ductility index evaluating method that considers such nature is demanded, but in this study, the existing ductility evaluating method that used displacement (Δ₈₀) in the down-coming stage at 80% after maximum load and one that used the displacement (Δₚᵉ) in stage where load begins to decrease rapidly after maximum load were used in order to evaluate the bending performance of singly reinforced beam without any compressive reinforcement.

\[
\mu_{\Deltaₚᵉ} = \frac{\Deltaₚᵉ}{\Deltaₘ} \quad \ldots(1)
\]
\[
\mu_{\Delta₈₀} = \frac{\Delta₈₀}{\Deltaₘ} \quad \ldots(2)
\]

The displacement ductility indices of each specimen calculated from load-deflection curve are shown in Table 7 and Fig. 10. When it comes to the displacement ductility index of bending member that used high-strength concrete, ductility index value of 3 or above is required in high seismicity area, and earlier researchers demand displacement ductility index of minimum 4. In addition Park and Ruitong reported that to obtain ductility for ordinary strength reinforced concrete beam by considering the tendency that ductility index decreases with increase in tensile steel, the ductility index for reinforcement ratio of ρ ≤ 0.75 ρₒ should be 2 or above.

In this study, as shown in Fig. 10, the ductility index µ₈₀ based on Δ₈₀ was 1.30 through 2.56, and the ductility index µₚᵉ based on Δₚᵉ was 1.23 through 2.47, indicating less value than the ductility index defined in existing researches, so it is determined that considering the fact that such results came out from ultra-high-strength concrete that assumes very brittle characteristics after maximum load and bending member with single reinforcement without any compressive reinforcement or shear reinforcement, ductility capacity also can be improved if compressive concrete is properly reinforced with compressive reinforcement and shear reinforcement. In addition, the above results indicated that as tensile steel ratio increased from 0.45 ρₒ to 0.75 ρₒ, ductility index decreased, and proper maximum tensile steel ratio to be considered to obtain minimum ductility for structural safety in 150 MPa ultra-high-strength concrete bending member is in the range of 0.55 ρₒ through 0.625 ρₒ.

Figure 11 shows the ductility values depending on the concrete strengths obtained from existing research results and the results of present study. This figure also shows the general characteristics of concrete strength such that the higher concrete strength is, the
lower the ductility for the same reinforcement ratio, indicating the brittleness of high-strength concrete. In case the strain of tensile steel is equivalent, for ultra-high-strength concrete of up to 120 MPa, ductility of singly reinforced beam can be 2.0 or above, but at 150 MPa, ductility was found to decrease. In other words, the higher the tensile steel ratio and the lower net tensile strain, the ductility index of member tends to decrease almost linearly, and thus in case of low reinforcement specimen, the behavior of member at final fracture was found to be significantly affected by reinforcement ratio.

**Compressive concrete strain**

The distribution of strain occurring from the end of compression block of each specimen at maximum load is shown in Fig. 12.

As shown in the figure, the strain at maximum load was at highest value at the location of 10 mm distance from compression end to tension side, and thereafter decreased toward tension side. The inflection points of compressive strain and tensile strain were found at the range of 80-115 mm from compression end, and the lower tensile reinforcement ratio and the higher reinforcement yield strength (SD 500), the higher the inflection point rise toward compression end.

In the above case, the compressive concrete area that corresponds to the stress of tensile steel decreases significantly in the bending member of 150 MPa ultra-high-strength concrete, and too small area of compressive concrete may lead to early fracture due to incapability to withstand the compressive force of structure, in designing bending member that used high-strength reinforcement like SD500 steel, it is determined that low tensile steel ratio would be recommended.

**Tensile steel strain**

The strain values of tensile steel by the load stages of each specimen are shown in Figs 13 and 14.

As shown in these figures, with SD 400 specimen, the strain of tensile steel exceeds 0.005 of the tension-controlled limit strain before and after maximum load, and compression controlled limit strain exceeds 0.002 of the compression-controlled limit strain at load of 30-40% of maximum load. In addition, in the case of SD 500 specimen, the strain of tensile steel cannot exceed 0.005 of the tension-controlled limit strain, but remains at the range of 0.0025-0.0035.

In SD 400 specimen, the strain values of specimens whose tensile steel ratios reach 0.45 $\rho_b$, 0.55 $\rho_b$ after maximum load were shown to be restored more or less, and thus the portion of stress of tensile steel was found to decrease due to the capacity of compressive concrete to hold the load. However, in case of specimen whose tensile steel ratio exceeds 0.625 $\rho_b$, the strain of tensile steel exceeds 0.005 of the tension-controlled strain limit, causing significant decrease in the contribution of compressive concrete.
for capacity to hold the load due to excessive reinforcement of tensile steel, and thus the portion of stress of tensile steel increases excessively. In addition, the more the yield strength of tensile steel increases, the less the strain of outermost tensile steel occurs, and cross-section exists within transition zone, but for this reason, brittle fracture of compressive concrete tends to be occurred more often particularly with increase in concrete strength, and that after all can lead to decrease of ductile capacity of member.

Maximum reinforcement ratio for minimum allowable strain in singly reinforced beam

If \( A_s \) (the amount of actually reinforced tensile steel) is greater than \( A_{sb} \) (the amount of reinforcement that reaches balanced strain condition), \( \alpha \) (the depth of compressive stress block) increases. In other words, \( c \) (neutral axis distance) becomes greater than \( c_b \), and comes down (see Fig. 15).

Therefore, when the concrete strain of compression end reaches \( \epsilon_u = 0.003 \) of ultimate strain, the net tensile strain of outermost tensile steel or tendon \( (\epsilon_s) \) will not reach compression-controlled limit strain \( (\epsilon_y) \) yet. In other words, such bending member reaches sudden a brittle fracture on compression side concrete without any symptom that indicates that external fracture is imminent when excessive load is applied. On the contrary, if the amount of tensile steel \( (A_s) \) is less than the amount of reinforcement in equilibrium condition \( (A_{sb}) \), the depth of compressive stress block \( (\alpha) \) decreases. In other words, neutral axis distance \( (c) \) is less than \( c_b \), and moves upward. (See Fig. 15)

Therefore, the net tensile strain of outermost tensile steel or tendon \( (\epsilon_s) \) exceeds 0.004 of the minimum allowable strain limit before the concrete strain \( (\epsilon_c) \) of compression end reaches ultimate strain \( (\epsilon_u = 0.003) \). In other words, in this case, sufficient precaution is delivered as significant deflection occur safer yielding of tensile steel before sudden fracture of compressive concrete occurs when excessive load is applied (ductile failure type). Therefore, in appreciation of the sufficient time interval to take measure before serious problem occurs, ductile fracture may be considered as desirable facture mechanism. For such reason, in earlier designing standard, 0.75 \( \rho_b \) the ratio \( (\rho/\rho_b) \) for balanced reinforcement ratio was specified as maximum allowable reinforcement ratio and tensile strain limit was implicitly applied to guarantee ductile fracture behavior, but ACI code provides that “in nominal strength, net tensile strain \( (\epsilon_s) \) should be the
minimum allowable strain of bending member or above.” The relations between the net tensile strain ($\varepsilon_t$) for single rectangular beam that used reinforcement of 400 MPa yield strength and ($\rho/\rho_b$) the ratio for balanced reinforcement ratio are as shown in Eq. (5) (see Fig. 16).

$$c = \frac{0.003d_j}{\varepsilon_t + 0.003} \quad \ldots (3)$$

$$a = \beta_c c = \frac{0.003\beta_c d_j}{\varepsilon_t + 0.003} \quad \ldots (4)$$

In balanced strain condition,

$$a_b = \frac{0.003\beta_c d_j}{(400/200,000) + 0.003} = 0.6\beta_c d_j$$

$$\rho = \frac{a}{a_b} = \frac{0.005}{\varepsilon_t + 0.003}$$

$$\rho = (\frac{0.005}{\varepsilon_t + 0.003})\rho_b \quad \text{or} \quad \varepsilon_t = \frac{0.005}{\rho / \rho_b} - 0.003 \quad \ldots (5)$$

According to comparison of the ductility indices of each specimen by the net tensile strain of tensile steel as shown in Fig. 10, in case tensile reinforcement ratio exceeds 0.55 $\rho_b$ regardless of the yield strength of reinforcement, that is, in case net tensile reinforcement strain does not reach 0.006, the ductility ratios of all the specimens decrease below 2.0, and that indicates that the ductile capacity of member decreases significantly due to sudden brittle fracture of compressive concrete after all. In addition, as shown in Fig. 11, up to 120 MPa of concrete compressive strength, ductility ratio can be 2.0 or above even in case the tensile reinforcement strain ($\varepsilon_t$) is 0.0037 ($\rho = 0.75 \rho_b$), but in case of 150 MPa ultra high-strength concrete, ductility ratio of 2.0 is met only in case tensile reinforcement strain is 0.0061 ($\rho = 0.55 \rho_b$).

Furthermore, according to the research results executed by You et al.\textsuperscript{17} on doubly reinforced beams, displacement ductility ratio $\mu_{\Delta80}$ was 2.87 in case tensile reinforcement ratio ($\rho = 0.732 \rho_b$) equivalent to minimum allowable strain 0.004 of current code is obtained, and 3.15 or so in case tensile reinforcement ratio ($\rho = 0.649 \rho_b$) equivalent to minimum allowable strain 0.005 of current code is obtained. According to such results, since the ductility ratio for singly reinforced beam with no compressive reinforcement is anticipated to decrease below the case of doubly reinforced beam, it is determined that the provisions will need be revised so that tensile steel shall be reinforced to meet the ductility ratio of 2.0 or above for singly reinforced beam and the ductility ratio of 3.0 or above for doubly reinforced beam, and in such case, proper range of maximum tensile steel ratio shall be maximum 0.55 $\rho_b$ or less, and that of tensile steel strain 0.006 or above (see Fig. 17).

**Conclusions**

This study was done on bending member of singly reinforced beam using 150 MPa ultra-high-strength concrete to verify the validity of the beam against the provision on the maximum reinforcement ratio of bending member which is newly revised and being
applied, and through comparative analysis of the bending experiment results and the study results of existing researchers, the following conclusions were drawn:

(i) In all specimens, up to maximum load, almost linear elastic behavior was occurred, but after maximum load, load suddenly decreased and brittle fracture occurred due to crushing of compression side concrete along with sudden decrease of load. However, the lower tensile steel ratio and the more the yield strength of reinforcement increase, the less the crushing occurred along with fewer occurrences of cracks and less width crack.

(ii) The ductile capacity of ultra-high-strength concrete beam of 100 MPa or above without compressive reinforcement decreased significantly rather than normal strength ($f_{ck}<40$ MPa) and high-strength concrete ($f_{ck}=40$ MPa $\sim$ 80 MPa). Thus, in case the strain of tensile steel is the same, the ductility index of singly reinforced beam was above 2.0 in ultra-high-strength concrete (to 120 MPa), but decreased at 150 MPa, indicating displacement ductility index ($\mu_{80}$) of 1.30 $\sim$ 2.56.

(iii) It was found that in case tensile reinforcement is done so that tensile steel ratio shall be above 0.6 $\rho_b$, and ultra-high-strength in compressive side, the area of compressive concrete required to counteract tensile stress was decreased. Here, member ductility may be decreased significantly after yielding load. Accordingly, it is judged that further reviews must be done on the restriction of maximum reinforcement ratio of present ACI code for the security of bending member ductility behavior.

(iv) To obtain the minimum ductility ratio of above 3.0 for double reinforced beam and above 2.0 for singly reinforced beam in reinforced concrete bending member with 150 MPa UHSC and 400 to 500 MPa yield strength steel, limit strain shall be set so that the net tensile strain of outermost tensile steel may be above 0.006 in excess of 0.005 which is specified in ACI code, and the tensile steel ratio is required to be 0.55 $\rho_b$ or less.

**Nomenclature**

$f_{ck}$ = compressive strength of concrete, MPa  
$f_y$ = yield strength of longitudinal reinforcement, MPa  
$M_{test}$ = test value of ultimate moment, kN-mm  
$M_{ACI}$ = moment calculate value of ACI standard, kN-mm  
$P_i$ = load of initial cracking, kN  
$P_y$ = load of member yielding(tension reinforcement), kN  
$P_{max}$ = maximum load of member, kN  
$P_{final}$ = the load significantly begins to reduce after maximum load, kN  
$\Delta_{ci}$ = deflection of initial cracking, mm  
$\Delta_y$ = deflection of member yielding, mm  
$\Delta_{fy}$ = deflection at $P_f$, mm  
$\Delta_{80}$ = deflection corresponding to 80% of the maximum load after maximum, mm  
$\mu_{80}$ = Displacement ductility index of $\Delta_{80}$ standard  
$\mu_{fy}$ = Displacement ductility index of $\mu_{fy}$ standard  
$\rho$ = tension steel ratio  
$\rho_b$ = balanced tension steel ratio

**References**