ULTIMATE STRAINS OF STRUCTURAL STEELS AGAINST DUCTILE CRACK INITIATION

Hanbin GE¹, Makio KAWAHITO² and Masatoshi OHASHI³

¹Member of JSCE, Associate Professor, Dr. Eng., Dept. of Civil Eng., Nagoya University
(Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)
E-mail: ge@civil.nagoya-u.ac.jp
²East Japan Railway Company (1-3-24, Shin-Chiba, Chuo-ku, Chiba 260-0031, Japan)
³Central Japan Railway Company (1-1-4, Meieki, Nakamura-ku, Nagoya 450-6101, Japan)

This paper aims to propose a criterion in terms of equivalent plastic strain or axial strain against ductile crack initiation for structural steels. For this purpose, tension test on round steel bars is simulated by finite element method and strain progression during the necking process until ductile crack initiation is investigated. Due to very large strain involved in this simulation, the common used constitutive model for structural steels is modified, and the Gurson’s micro void model is employed to consider the material deterioration. As a result, a prediction criterion for structural steels is put forward in terms of stress and equivalent plastic strain. Moreover, a relation between local strain and global strain is obtained and ultimate strains are proposed to evaluate ductile crack initiation for fiber analysis of steel structures in seismic design.

Key Words : ductile crack initiation, structural steel, brittle fracture, micro-void model, ultimate strain

1. INTRODUCTION

Recent severe earthquakes have demonstrated the vulnerability of steel structures to brittle fractures. Among them, fractures in steel bridges (e.g., Fig.1) were witnessed in the 1995 Hyogoken-Nanbu earthquake(1)-⁴). This fact indicates that beside local buckling, brittle fracture is another big problem in steel structures under severe earthquake excitations.

It has been realized by many researchers that failure modes of steel bridge piers under strong earthquakes can be either failure due to brittle fracture in relatively thick-walled structures or failure due to local buckling in thin-walled structures. It is worthy to note that in order to get a high ductility in steel bridge piers, relatively thick-walled sections are becoming more and more popular in the practical seismic design instead of relatively thinner sections. This makes it more necessary to take into account fracture failures in steel piers. However, existing capacity prediction procedures developed for single column type and portal frame type steel piers account for only those failures caused by local buckling. A capacity prediction procedure for steel bridge piers, which considers fracture at bases or corners of piers, as well as local buckling, is lacking. To develop such an evaluation procedure for engineering application, it is imperative to make mechanism of the brittle fracture clear. With regard to this aspect, many researchers have paid their attentions on reproduction of brittle fracture, development of structural details and proposal of new steel material with high toughness⁵)-¹⁵).

According to post-earthquake inspections and some results of laboratory tests, the mechanism of such failures in steel members sustained plastic deformation is characterized by a sudden fracture triggered by ductile cracks initiated under large plastic strain reversals. The failure procedure is believed to be a three-phase sequence, namely, 1) initiation of a ductile crack at a strain concentration hot spot, 2) stable growth of the ductile crack penetrating into thickness and width under large plastic strain cycles, and 3) final cleavage fracture in a brittle fracture mode when critical size of the crack is reached during propagation.

Ductile cracking in metals is a traditional topic in fracture, which have attracted researchers’ interests in the past several decades and many investigations have been carried out by both theoretical modeling and experiments(1⁶)-²²). However, it was mainly a problem considered in such fields as material proc-
essing and mechanical engineering until the 1994 Northridge and 1995 Hyogoken-Nanbu earthquakes demonstrated the ductile crack problem in earthquake engineering, in which ductile crack initiation is believed to be the first step to cause final cleavage fracture during severe earthquake excitations. In the field of steel building structures after the two earthquakes, Kuwamura et al.\textsuperscript{23)-30}) and Ono et al.\textsuperscript{31}) conducted a series of studies on the crack initiation condition and corresponding criteria were obtained.

This study is intended to establish a criterion against ductile crack initiation for structural steels normally used in current civil engineering practice in Japan, in a form convenient for practical application. To this end, numerical simulations are carried out on round steel bars to study mechanism of ductile crack initiation. In the analysis, the Gurson’s micro-void model\textsuperscript{20)-22)} is employed to consider the material deterioration as used in a previous study by Obata et al.\textsuperscript{32)} In determining a judgment criterion for ductile crack initiation, numerical results are compared with previous experimental results\textsuperscript{31}). As a result, a prediction criterion for structural steels is put forward in terms of stress and equivalent plastic strain. Moreover, a relation between local strain and global strain is obtained and ultimate strains are proposed to evaluate ductile crack initiation for fiber analysis of steel structures in seismic design.

2. OUTLINE OF NUMERICAL ANALYSIS

(1) Stress triaxiality and equivalent plastic strain
McClintock\textsuperscript{16)} proposed a theoretical model for micro-mechanical modeling of ductile crack formation on the basis of voids growth, in which stress triaxiality, $\tau$, and equivalent plastic strain, $\varepsilon_{eq}$, are considered to be two key factors. Thereafter, extensive investigation by Mackenzie and Hancock in a combination of experimental and theoretical microscopic model\textsuperscript{17,18)} confirmed the role of both factors in ductile fracture. In this study, $\tau$ and $\varepsilon_{eq}$ defined by Eqs.(1) and (2) are also employed to evaluate the ductile crack initiation, as used in recent papers by Kuwamura et al.\textsuperscript{23)-30)}.

$$\tau = \frac{\sigma_h}{\sigma_{eq}} \quad (1)$$

$$\varepsilon_{eq} = \int \frac{2}{9} [(d\varepsilon_{ps}^1 - d\varepsilon_{ps}^2)^2 + (d\varepsilon_{ps}^2 - d\varepsilon_{ps}^3)^2 + (d\varepsilon_{ps}^3 - d\varepsilon_{ps}^1)^2] \quad (2)$$

in which, $\sigma_h$ and $\sigma_{eq}$ are the hydrostatic stress and equivalent stress, respectively; $d\varepsilon_{ps}^1$, $d\varepsilon_{ps}^2$ and $d\varepsilon_{ps}^3$ are incremental principal plastic strains. $\sigma_h$ and $\sigma_{eq}$ are defined by

$$\sigma_h = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \quad (3)$$

$$\sigma_{eq} = \frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (4)$$

where $\sigma_1$, $\sigma_2$, and $\sigma_3$ are principal stresses.

(2) Analytical model
When thick-walled sectional steel structures are subjected to large plastic strain caused by either earthquake excitations or cyclic loading, ductile crack is likely to occur at bases and/or corners with serious strain concentration and then grow to a critical size to cause a final brittle fracture. However, it is quite difficult to simulate the crack initiation by performing a numerical analysis on an entire structure. For this reason, as a first step of such an effort of making the ductile crack initiation mechanism clear, tension test on round bars with defects is simulated in this study. The defect is assumed to be an ideal notch with a combination of different notch depth ($d = 1$ or 2 mm) and notch root radius ($R$) ranging from 0.25 to 10mm as shown in Table 1. This approach is similar to a procedure adopted by Kuwamura et al.\textsuperscript{25}).
Analysis is carried out on round bars by general-purpose FEM program ABAQUS). Due to the axisymmetry, only half the round bar is modeled using the axisymmetric element. The tension test process is simulated by displacement-controlled loading at one end. Geometry and boundary conditions of the model (8mm in radius and 15mm in length) are shown in Fig.2. Because this analysis involves very large strain far beyond yielding point, the nonlinear formulation option, which allows for large deformation provided by ABAQUS numerical solution, is incorporated.

Three different steel grades, i.e., SS400, SM490 and SM570, which are usually used in current civil engineering steel structures in Japan, are considered in this work. A constitutive model for the structural steels is adopted here (see Fig.3), which consists of an elastic region, a yielding plateau and a consequent strain-hardening region, as expressed in terms of nominal stress and nominal strain by

\[
\sigma = \sigma_y \left( \frac{\varepsilon}{\varepsilon_y} \right)^n \quad (6)
\]

in which \(n\) is the strain hardening parameter. It should be noted that stress and strains in this equation are in terms of true stress and true strain. For the three steels, the power-law hardening relationship is employed where strain is larger than \(\varepsilon_y\). Parameter \(n\) for each steel is determined by assuming that the power-law hardening SS curve passes the point \((\sigma_y, \varepsilon_y)\), which is the end of the conventional constitutive curve. Values of \(n\) determined in such a way are given in Table 2, together with ultimate strains (true strains) obtained from coupon tests. Thus, the modified constitutive law is then composed of the original relationship above till \((\sigma_y, \varepsilon_y)\) and a power-law curve expressed by the above equation from \(\varepsilon_y\), as shown in Fig.3.

(3) Micromechanical mechanism of ductile crack

It is generally accepted that ductile crack initiation is a progress of micro-void nucleation, growth and coalescence (Fig.4). Under large straining, voids are generated around inclusions or second phase particles in metals, and grow due to the presence of high plastic strain until the expanding voids coalesce to form a macroscopic crack, i.e., ductile crack. Moreover, ductile cracking can occur in a case even without any existing flaws which were prevailing in the fractured pre-Northridge steel connections.

Necking is followed by ductile fracture initiated at the location subjected to a combination of high plastic strain and stress triaxiality. Modified Gurson’s model is employed here to evaluate failure during the necking process, in which the yield criterion due to void volume fraction evolution is expressed by

\[
\left( \frac{\sigma_{eq}}{\sigma_y} \right)^2 + 2q_f \cosh \left( \frac{3}{2} q_1 \frac{\sigma_{eq}}{\sigma_y} \right) - \left(1 + q_1^2 f^2 \right) = 0 \quad (7)
\]

in which \(f\) is the micro-void volume fraction defined by dividing volume of voids \(V_{void}\) with the consid-

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**Table 1** Notch dimensions.

| Notch depth (\(d\)) | 1.0mm, 2.0mm |
|---------------------|--------------|
| Notch radius (\(R\)) | 0.25mm, 0.5mm, 1.0mm, 2.0mm, 2.5mm, 3.0mm, 5.0mm, 10.0mm |

**Table 2** Material properties.

| Steel kind | \(\frac{\sigma}{E} \) | \(E/E_{st} \) | \(\varepsilon_{st}/\varepsilon_y \) | \(\varepsilon_y \) | \(n\) |
|------------|------------------|---------------|----------------|--------------|
| SS400      | 0.06             | 40            | 10             | 19.8%        | 0.106       |
| SM490      | 0.06             | 30            | 7              | 18.9%        | 0.131       |
| SM570      | 0.02             | 100           | 3              | 16.5%        | 0.116       |
considered element volume \( V_{\text{element}} \) as
\[
f = \frac{V_{\text{void}}}{V_{\text{element}}}
\]  
(8)
It is obvious that when \( f=0 \) (containing no voids), Eq.(7) is equivalent to von Mises yielding criterion. Moreover, \( q_1 \) and \( q_2 \) are parameters and were set to be 1.0 in the original Gurson’s model. After calibration, \( q_1=1.5 \) and \( q_2=1.0 \) was proposed for the modified model20).

The void volume fraction \( f \) is determined by strain, and material deteriorates when \( f \) increases. Evolution of void volume fraction accounting for micro-void nucleation and growth is expressed by
\[
df = df_{\text{nucleation}} + df_{\text{growth}}
\]  
(9)
\[
df_{\text{nucleation}} = A f_{\text{eq}}
\]  
(10)
\[
df_{\text{growth}} = (1-f)(d\varepsilon^p_{11} + d\varepsilon^p_{22} + d\varepsilon^p_{33})
\]  
(11)
Here \( df \) denotes an increment of \( f \), and \( d\varepsilon^p_{11}, d\varepsilon^p_{22}, d\varepsilon^p_{33} \) are principal plastic strains. Also, the parameter \( A \) in Eq.(10) is chosen that nucleation follows a normal distribution expressed as
\[
A = \frac{1}{E_t} \left( 1 - \frac{1}{E} \right) \frac{f_N}{s_N \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\varepsilon^p_{\text{eq}} - \varepsilon_N}{s_N} \right)^2 \right]
\]  
(12)
Here, \( E_t \) = tangent modulus; \( f_N \) = void volume fraction of void nucleation particles; \( \varepsilon_N \) = mean strain for nucleation and \( s_N \) = standard deviation. Void nucleation is found to initiate when void volume fraction \( f \) reaches a critical value \( f_C \), which is of the order of 0.15 for steels, and other parameters were proposed to be \( f_N=0.04 \), \( \varepsilon_N=0.3 \) and \( \sigma_N=0.1 \)21). In this analysis, the initial void volume fraction is assumed to be zero. Once the void volume fraction \( f \) is determined as shown above, then the stress can be evaluated from Eq.(7).

3. ANALYTICAL RESULTS AND DISCUSSIONS

As described above, when the member is tensioned to a high plastic strain level, voids are formed and grow up. In this section, analytical results are presented and discussed to show how the void grows up and how the void affects the stress triaxiality and equivalent plastic strain.

(1) Effect of void evolution

Fig.5 shows the effect of void evolution on the stress triaxiality and equivalent plastic strain of an element where void’s growth is the earliest. As is seen from Fig.5(a), the stress triaxiality is reduced in the case with a sharp notch shape (\( R=0.25 \)mm), compared with that without considering the void growth. However, the relation is gradually reversed as the notch radius is increased. In the case of \( R=2.0 \)mm, the stress triaxiality of the model considering the void growth is growing. In this sense, it can be said that to accurately predict the ductile crack initiation, not only the defects but also the deterioration in the material (e.g., the section loss due to void
growth) should be considered.

(2) Effect of material kind and notch shape

a) Effect of material kind

Fig. 6 shows how the void growth differs for different steel material. It should be noted here that the surrounding of the notch is magnified so that the difference can be observed clearly.

Shown in Fig. 6 is distribution of the void volume fraction $f$ when its maximum value reaches 15% for a model of $R=0.25$ mm. The gray zone is the place where $f$ exceeds 15%, and a red zone hits just 15%. For SS400 and SM490 materials, it is observed that $f$ exceeds 15% firstly on the surface along a minimum section. Namely, the strain concentrates and the void grows up on the deepest part of the notch surface. Moreover, the place where the void growth is remarkable can also be seen on the surface. As for the growth at this spot, SS400 is larger than SM490. In the case of SM570, the critical location is observed at a spot a little above from the minimum section. This finding may result from a difference in the yield point of the material. Furthermore, it can be concluded that regardless of the steel material, the void distribution is centered on the deepest part of the notch surface and extends radially.

b) Effect of notch depth

Shown in Fig. 7 are models with the same notch radius ($R=0.25$ mm) but different notch depths ($d=1.0$ mm and 2.0 mm). Moreover, the steel kind is SM490. The void distribution when the maximum value of $f$ exceeds 15% is shown in this figure. It is understood that places to which void grows up most are different even if the notch radius is the same. Moreover, the notch depth also affects the relation of the average strain $\varepsilon_{av}$ (elongation divided by length) and the void growth. At $f=15\%$, the average strain is about 10.3% in the model of $d=1.0$ mm while 4.7% in the model of $d=2.0$ mm. This fact indicates that the strain concentration is significant and the stress tri-
axiality is high as the notch depth becomes large.

c) Effect of notch radius

Fig. 8 shows the void distributions of three models with the same material (SM490) and notch depth ($d=1.0\text{mm}$) but different notch radius ($R=0.25, 2.0$ and $3.0\text{mm}$) when $f$ reaches 15%. According to this figure, it is observed that void grows up only around the notch in the case of $R=0.25\text{mm}$. On the other hand, void doesn't grow up locally but gradually distributed from the minimum section in the cases of $R=2.0$ and $3.0\text{mm}$. Moreover, the void growth seen is slightly deviated from the surface of the minimum section in the case of $R=2.0\text{mm}$. Comparing the void growth parts between $R=0.25$ and $2.0\text{mm}$, a tendency which void’s maximum growth point shifts gradually to the center can be seen as $R$ is increased. In contrast, the biggest void growth in the center part along the minimum section is seen in the case of $R=3.0\text{mm}$.

As for the void evolution, it extends radially from the deepest part where void grows up rapidly in the case of $R=0.25\text{mm}$. Void’s extension spreads widely in the case of $R=2.0\text{mm}$ although it extends similarly as in the case of $R=0.25\text{mm}$. Then, void began to rapidly grow up from the center part in the minimum section. In the case of $R=3.0\text{mm}$, the void is firstly observed on the surface of the bottom and then extended radially to some degree and finally it hardly grows up. On the other hand, voids near the center part in the minimum section come to grow up rapidly suddenly. Accordingly, cracks can be divided into two types: bottom surface type in a sharp notch and internal type in a blunt notch. This phenomenon is quite similar to experimental results by Kuwamura et al.\textsuperscript{23} and thus it can be said that the present numerical model is able to reproduce the experimental results well, and the use of the void growth concept is effective to investigate the mechanism of the ductile crack initiation. Moreover, as is seen from configuration of the element around the notch, the level of necking process is smaller in the case of $R=3.0\text{mm}$ than in the case of $R=0.25\text{mm}$. This can also be explained by the average strain. The values of the average strain at $f=15\%$ are 19.2% and 11.9% respectively for $R=3.0$ and $R=0.25\text{mm}$. This is because that in the models with a sharp notch the strain concentrates locally and the void growth is promoted while the strain concentration can be decreased when the notch becomes blunt. A more important thing is that investigating the void evolution is possible to specify the place of ductile crack initiation either from the surface or from the center part in the minimum section.

(3) Judgment criterion of ductile crack initiation

In this study, a critical void volume fraction at which crack occurs is determined by referring to the experiment result by Ono et al.\textsuperscript{31} It should be noted that the size of the test pieces used in that experiment and analytical models in this numerical study is the same. In the experiment, only the one where the crack generation from the surface of notch bottom was confirmed has been treated. Therefore, the critical void volume fraction is first determined from the crack bottom surface type, and then applied to the crack internal type. Based on obtained results, an equation for the ductile crack initiation condition is finally proposed for both two types.

In Fig. 9, relations between the average strain and void volume fraction of an element in which $f$ reaches 15% at first are shown for the cases of $R \leq 2.0 \text{mm}$. The element is the one on the surface in the minimum section in the cases of $R=0.25$ to $1.0\text{mm}$ while it is an element that entered from the surface of notch by about 1mm in the cases of $R=2.0\text{mm}$. Experimental results by Ono et al. are also plotted in the figure. It should be noted that average strains from the experiment are those obtained when the crack is actualized to the surface of notch.

As can be seen from the figure, in the models of $R=0.25\text{mm}$ made of SS400, the void volume fraction hardly changes or even decreases after it reaches a certain value. It is noted that $f$ reaches 15% earliest in the attention element, and after that the growth in this element stops but in another element $f$ grows up rapidly. For the model made of SM490, $f$ keeps unchanged from a certain value. This is because the strain level is far larger than the ultimate strain and the analysis failed to converge. However, because the range of $f \leq 15\%$ is important as described later, and thus there is especially no problem on developing the ductile crack initiation conditional expression in this analysis.

In all the cases $f$ grows up rapidly by almost between 10% and 20% regardless of the steel material, notch radius and notch depth. Moreover, when the notch radius is small, the value of the average strain when void grows up rapidly has become small. This is because the strain concentration and stress triaxiality constraint take part mutually and the ductile crack occurs in a discontinuity location. Therefore, the smaller radius or deeper depth is, the more the strain concentrates on the notch surface and the stress triaxiality constraint rises. The point that should be paid attention is that the void volume fraction grows up rapidly at about 10% in the models of $R=0.25$ and 0.5mm where the cracks are confirmed earliest. In summary, the following can be said from above discussions:

1) In the experiment, the crack was observed on the surface of notch earliest when $f$ exceeded 10% a
little.

2) In almost all cases in this analysis, \( f \) grows up rapidly between 10% and 20%.

According to above two points and a fact that the ductile crack initiation phenomenon accompanies inevitably a big scatter, and from the viewpoint of the safety side, it is appropriate to assume that a ductile crack occurs when \( f \) reaches 10% in this analysis, instead of 15% as previously proposed by Tvergaard and Needleman\(^{20}\). That is, the limit value of the void volume fraction is assumed to be 10% at which the crack occurs.

(4) Classification of crack bottom surface type and crack internal type

As described previously, depending on the level of the notch sharpness, the crack may be initiated either from the surface of notch or from the center part in the minimum section. A boundary of a crack bottom surface type and a crack internal type is examined by using the condition that the crack occurs by \( f \) = 10% as defined in the foregoing section.

Fig.10 is a result of the parametric analysis concerning the notch radius and depth. The horizontal axis is notch depth, and the vertical axis is notch radius. The inside for the shaded portion stands for the crack bottom surface type, and other parts show the crack internal type. In the case of SS400, a difference of 0.8mm in the radius can be observed between \( d=1.0 \) and 2.0mm. Moreover, the result of models with deep depth (\( d=2.0 \)mm) does not depend on the steel kind but for those with shallow depth (\( d=1.0 \)mm) the influence of the steel material is obvious. Accordingly, a classification of the crack bottom surface type and the crack internal type is able to be made by considering the void growth as mentioned above.

(5) Ductile crack initiation condition

In this section, the analytical results of all the cases are employed to propose a ductile crack conditional expression that considers both the crack internal type and the crack bottom surface type.

The stress triaxiality and equivalent plastic strain at the ductile crack initiation of all the analyzed models are shown in Fig.11. For models failed in the crack bottom surface type, data are overcrowded in a narrow range of \( \tau \), namely, the stress triaxiality is distributed within a range from 0.4 to 0.6, and the corresponding equivalent plastic strain is from 0.7 to 0.9. On the other hand, the range of \( \tau \) is large in models failed in the crack internal type, and the equivalent plastic strain is very small and limited within a range of 0.33~0.55. The following ductile crack initiation conditional expression is obtained by the nonlinear least square method.

\[
\varepsilon_{eq}^p = 0.775 \exp(-1.5\tau) + 0.422 \tag{13}
\]

This equation is also plotted in Fig.11.

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Since Eq.(13) is expressed in terms of the equiva
lent plastic strain and stress triaxiality, it is difficult to be directly applied for practical engineering application. Therefore, it is necessary to obtain a correlation between the locally obtained plastic strain and the global strain.

The global strain is assumed to use the axial strain obtained in a point far away from the notch to reduce its influence as much as possible. In the analytical model used for the foregoing investigations, however, the correlation of the global strain and the equivalent plastic strain is not good even in a point considerably away from the notch when the notch radius increases. Then, the analytical model has to be made longer. It is confirmed that the local plastic strain, stress triaxiality as well as the proposed equation are not affected by the length of round bars. That is, it seems that the change in length does not influence the ductile crack initiation conditional expression. Therefore, the axial strain in a point 60mm away from the minimum section is assumed to be the global strain by using an analytical model of 60mm in length × 8mm in radius to clarify the relation between the global and equivalent plastic strains.

As an example, the relation of the global and equivalent plastic strains is shown in Fig. 12 for models made of SM490 with the notch radius ranging from 0.25 to 2.0mm. Here, the following approximation formulas that give relations of the global strain and the equivalent plastic strain are obtained by the nonlinear least square method.

\[
\begin{align*}
\epsilon_{\text{eq}} &= 252\epsilon_x^2 \\
\epsilon_{\text{eq}} &= 125\epsilon_x^2 \\
\epsilon_{\text{eq}} &= 76.1\epsilon_x^2
\end{align*}
\]

(14)

On the other hand, in the analysis for seismic design purpose in which the fiber model employing the beam element is often used, the axial strain can be easily output but it is not the case for the equivalent plastic strain. Therefore, it will be convenient if ultimate strain against the ductile crack initiation can be expressed by the axial strain (global strain). To this end, a procedure is established with the help of Eqs.(13) and (14). As an example of SM490, the range of the global strain is decided as shown in Fig. 13. Plot (a) is the relation between the global strain and equivalent plastic strain by Eq.(14), and plot (b) is the stress triaxiality and equivalent plastic strain when a ductile crack occurs together with Eq.(13).

As mentioned previously and shown in plot (b), the equivalent plastic strain when the crack occurs is 0.7-0.9 for the crack bottom surface type while 0.35-0.55 for the crack internal type, and it is clear that their ranges are narrow. Then, this area is shifted...
to plot (a), and as a result a range of the global strain where a ductile crack occurs is worked out. This range gives the area of ultimate strains against the ductile crack initiation. Table 3 shows such ranges obtained for each steel material. For instance, taking the lower bound value for the crack bottom surface type in the design, the following equations are obtained.

\[
\begin{align*}
\varepsilon_g &\leq 5.4\% \quad \text{for SS400} \\
\varepsilon_g &\leq 7.7\% \quad \text{for SM490} \\
\varepsilon_g &\leq 9.8\% \quad \text{for SM570}
\end{align*}
\]

It is judged that a ductile crack occurs when the axial strain reaches 5.4\% (47.4 \varepsilon_g) for steel members made of SS400 in the analysis that uses the fiber model.

5. CONCLUSIONS

This paper was intended to present a prediction criterion for structural steels against ductile crack initiation with the help of FEM necking process simulation on a round bar. In the analysis, void evolution was introduced as a technique for considering the section loss in the large strain range. The failure criterion of judging ductile crack initiation was decided using the void volume fraction based on the previous experimental results. Furthermore, the correlation of a local plastic strain and a global strain was shown, and the ultimate strains against the ductile crack initiation were proposed. Following conclusions can be drawn from the work presented above.

1. The crack bottom surface type and the crack internal type were able to be caught by present numerical method considering the void growth.
2. A failure criterion of judging the ductile crack initiation was determined as \( f_C = 10\% \) based on the numerical results and available experiment data.
3. The ductile crack initiation conditional expression was proposed.
4. The ultimate strains against the ductile crack initiation were obtained for the analysis that uses the fiber model from the correlation of a global strain and the equivalent plastic strain.

This research is a basic research on the development of a unified seismic design method that can be used to check failures by either local buckling or brittle fracture, and the following are enumerated as problems in the future. It is necessary to verify the correlation of a material level and a structural level so that the findings are applicable to members and structures. For instance, the structural detail coefficient, in which the characteristic of the corner part is considered, might be needed through an extensive investigation. Also, the criterion proposed in this work is yet only valid for monotonic loading case. As for the cyclic situation, further work should be performed to correlate the two cases. Moreover, this is a theoretical work by FEM computation, which needs more verification from tests on steel members and structures.

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