Damage concept for evaluating ductile cracking of steel structure subjected to large-scale cyclic straining

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Abstract

Evaluation of ductile crack initiation in steel welded structures subjected to seismic loading is crucial for structural design or safety assessment to prevent brittle fracture induced by ductile cracking. Observation of ductile crack initiation behavior of round-bar specimens with/without circumferential notches tested in single tension revealed that the main controlling factor for ductile cracking in the employed two-phase steel is not growth of voids induced by large inclusions, but nucleation of micro-voids in a soft phase (Ferrite phase) near the Ferrite–Pearlite interface after large-scale plastic straining. The material damage concept under reverse loading, which correlates the material damage for micro-void nucleation to macro-scale mechanical parameters, was proposed in consideration of two aspects of the Bauschinger effect: (a) a mechanical aspect which influences deformation and stress/strain behaviors in steel structures, (b) a material damage aspect caused by dislocation behavior. A new criterion for ductile cracking of structural members under cyclic loading was proposed on the basis of the proposed effective damage concept and ‘two-parameter criterion,’ which can be applied to the steel structures under increasing load in a single direction. The validity of the advanced two-parameter criterion was verified by subjecting round-bar specimens to cyclic loading tests along the axial direction and cross-shaped specimens to cyclic 3-point bending tests. Consequently, the advanced two-parameter ductile cracking criterion was found to be a transferable criterion for evaluation of critical loading cycle of structural members from small-scale tensile test results.

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1. Introduction

Brittle fracture of steel structural components should be prevented even under large-scale seismic loading. Especially, large-scale straining at the stress/strain concentration region in structural components frequently lowers both the ductility and fracture toughness of structural steel, thereby facilitating the initiation of local ductile cracking and subsequent crack extension by cyclic loading, which can lead to brittle fracture [1,2]. An important measure for preventing brittle fracture of steel structure is critical design for preventing the initiation of ductile cracking under large-scale cyclic loading.

The general behavior of ductile failure usually involves the formation of voids around large inclusions or second-phase particles and the subsequent growth of the voids to final coalescence. In an effort to develop a comprehensive criterion for ductile failure, several theoretical models of void growth has been proposed, including Thomason’s model [3], Mc Clintock’s model [4,5] and Rice’s and Tracey’s model [6], for the case where void growth is the dominant mechanism for ductile fracture in materials of interest. In view that the growth stage of voids would be affected by the hydrostatic component of stress conditions, in Mc Clintock’s model ductile failure initiation strain was first related with stress triaxiality (the ratio of mean stress to equivalent flow stress). On the basis of these models, the dependence of stress triaxiality on ductility for various metals has been considered through employment of small-scale tensile specimens with circumferential notches tested under single tension [7–10].

Meanwhile, numerous studies have been conducted on the effect of prestreaining on ductile failure. As is generally
known, ductility of a metal depends considerably on the prestraining conditions. Retained ductility generally decreases in approximately inverse proportion to the amount of tensile prestrain [11–13]. However, as compared with tensile prestrain, compressive prestrain usually has a smaller effect in reducing retained ductility, over a wide range of prestrain levels [11–14]. Such dependence of ductility on prestraining conditions has been qualitatively interpreted from the Bauschinger effect of materials in terms of differences in mechanical properties [14,15]. However, only a few studies have attempted to quantitatively assess critical ductile crack initiation for steel structures subjected to large-scale cyclic loading as well as prestraining [16]. This might be due to a low level of understanding of material damage for ductile cracking of structural steels under large-scale straining as well as under monotonic straining.

This study proposes a damage concept for ductile crack initiation of structural steel from experimental clarification of a mechanism for ductile cracking. This damage concept was employed in the ‘two-parameter ductile cracking criterion’ suggested by the authors [17,18] for critical assessment of steel structures subjected to monotonic straining. The main concept is focused on evaluation of the Bauschinger effect, which can make a crucial contribution not only to the stress/strain field but also to the material damage for ductile cracking. The validity and transferability of this ‘advanced two-parameter criterion’ was discussed by conducting cyclic loading tests and FE-analysis for round-bar specimens and bending specimens with stress/strain concentration regions. These specimens were selected for demonstration of the applicability of this criterion when ductile cracking could occur from the specimen center (round-bar) and from the specimen surface (bending specimen).

2. Ductile crack initiation behavior and critical conditions in small-scale test specimens under single tension

2.1. Ductile cracking controlling behaviors

Small-scale tensile specimens were used for investigating the ductile cracking behavior of structural steel with thickness \( t = 13 \text{ mm} \). The steel used is SM490YB steel, which has two phases with a strength mismatch; that is, Ferrite and Pearlite, as shown in the microstructures in Fig. 1. Table 1 shows the chemical composition of the steel, and Table 2 lists its mechanical properties.

![Fig. 1. Microstructures of SM490YB (Ferrite–Pearlite) steel used.](image)

Table 1
Chemical composition of SM490YB steel used

| Chemical composition (%) | C   | Si  | Mn  | P   | S   | Cu  | Ni  | Cr  | Mo  | V   | B   | \( C_{eq} \) |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------|
|                         | 0.17| 0.33| 1.37| 0.018| 0.018| 0.01| 0.07| 0.06| 0.008| 0.002| 0.0001| 0.43 |

\[ C_{eq} = C + \frac{\text{Mn}}{6} + \frac{\text{Si}}{24} + \frac{\text{Ni}}{40} + \frac{\text{Cr}}{5} + \frac{\text{Mo}}{4} + \frac{\text{V}}{14}. \]
the growth and coalescence of numerous nucleated micro-voids from the central region in the necked or pre-notch root section, leading to final ductile failure.

In contrast, in sharp notched R0.2 and R0.1 specimens, ductile cracking occurred from the surface of the pre-notch root. Fig. 3(b) shows micrographs near the pre-notch root in sectioned R0.1 specimen unloaded at a particular applied strain level near the maximum loading level. No conspicuous voids are visible near the ductile crack. The ductile cracking occurs from the pre-notch root associated with growth and coalescence of nucleated micro-voids along a local shear band oriented at an angle of about 45° in relation to the tensile axis. Surface cracking in the sharp-notched specimen implies shear mode ductile cracking, which is in contrast with the equiaxed tensile mode of ductile cracking from the specimen center.

The damage evolution which controls the ductile cracking was observed in detail, with focus placed on void nucleation until ductile cracking. Fig. 4 shows etched micrographs observed by SEM on the longitudinal and vertical sections in the middle of the smooth-bar specimen after 105% tensile plastic straining just before 122% ductile cracking strain; plastic strain was estimated at the middle of the minimum cross-section of the specimen analyzed by the FE-method presented in Section 2.2. Numerous micro-voids measuring approximately 1 μm were found to nucleate in the soft Ferrite phase near the Ferrite–Pearlite interface. This nucleation behavior of

| Mechanical properties of SM490YB steel used |
|---------------------------------------------|
| s_y (MPa) | s_T (MPa) | Y (%) | T (%) | YR (%) | El. (%) | Hv |
| Ferrite   | Pearlite  |       |       |        |        |    |
| 344       | 540       | 64    | 1706   | 31     | 198     | 276 |

\*s_y*, lower yield stress; \*s_T*, tensile strength; \*Y*, \*s_y/s_T*, \*T*, uniform elongation; \*El.*, elongation (G.L. = 36 mm, Dia. = 6 mm); \*Hv*, average Vickers hardness (Load: 25 g).
micro-voids could be due to the highly condensed pile-up of dislocations near the interface of microstructures with mismatch in strength. Moreover, almost no such micro-voids or other larger voids were observed before 105% plastic straining. This indicates that ductile cracking can be controlled by nucleation of micro-voids in the employed steel, not by the growth of larger voids, which is the conventionally interpreted mechanism of ductile cracking.

2.2. Two-parameter criterion for ductile crack initiation

The mechanical conditions for ductile crack initiation were examined by using the experimental results for small-scale tensile specimens on the basis of ‘two-parameter criterion,’ in which plastic strain and stress triaxiality were adopted as mechanical parameters that control ductile cracking [3,4].

All types of tensile specimens were subjected to finite element analysis. The geometry and size of FE-models are the same as those used in the tensile tests. In the FE-model, two-dimensional axi-symmetrical elements were used. The size of the elements on the minimum cross-section is the same in all types of specimens; 0.03 mm (radial direction) × 0.03 mm (longitudinal direction), which approximately corresponds to the average grain size of the employed steel. The FE-analysis was conducted by using nonlinear FE-codes, ABAQUS Ver. 5.8. Yielding condition in the FE-analysis followed von Mises yield criterion for isotropic/kinematic (combined) hardening materials as presented in Section 3.

In using the stress and strain fields in the specimens as obtained by FE-analysis, the mechanical conditions under which the crack initiation mechanisms can operate were considered. In all specimens under tensile loading until ductile cracking, the equivalent plastic strain ε_pl at the crack initiation point in the specimen was related with the stress triaxiality σ_m/σ (σ_m is mean stress and σ is von Mises equivalent stress). The estimated parameters were adopted at the mid-point in smooth, R2, and R1 specimens and at the first element of the pre-notch root in R0.2 and R0.1 specimens, these locations corresponding to the ductile crack initiation area. In this study, ductile crack initiation from the specimen surface was defined as the loading level at which a ductile crack measuring 0.05 mm was found in experiments. As shown in Fig. 5, the critical local equivalent plastic strain required to initiate ductile cracking depends largely on the stress triaxiality when the ductile crack nucleates from the specimen center. When the stress triaxiality is increased, critical strain decreases exponentially. In the case where ductile cracking occurs from the surface of the notch root, the critical strain level is almost independent of the radius of pre-notch root, and the stress triaxiality is constant and lower than that for center cracking specimens. The difference in ductile cracking controlling parameters between ductile cracking from the specimen center and ductile cracking from the surface could be due to the difference in the ductile cracking modes associated with the respective stress–strain states; almost no gradient is observed in the ε_pl and σ_m/σ distributions in the radial direction near the central region of the net-section in center cracking specimens, whereas a considerably large gradient is produced near the surface of the pre-notch root in surface cracking specimens.

3. Proposal of effective damage concept

The critical condition for ductile cracking obtained in Fig. 5 would be transferable to the estimation of ductile cracking load of specimens of any other geometry subjected to monotonic loading. Namely, ductile cracking for any structural members can be predicted with high accuracy by estimating the stress/strain field by FE-analysis. However, in the case where the applied stress is reversed under cyclic loading, influence of the Bauschinger effect should be taken into account in relation to not only the stress/strain field, but also the material damage related to ductile cracking.

As suggested from observation of micro-voids in Section 2.1, the material damage related to ductile cracking should be correlated with the material behaviors up to micro-void nucleation; the material damage is assumed to correspond to the evolution of dislocation density near the Ferrite–Pearlite interface. On the other hand, the Bauschinger effect of materials had been recognized to be caused by mainly the accumulation of long-range internal stress due to pile-up of dislocations around obstacles, which in the steel of interest is the Ferrite–Pearlite interface. In the case where the applied stress is reversed, some of the piled-up reversely mobile dislocations move in the opposite direction [19–23], and after a certain straining, form the equivalent dislocation structures with that before reverse loading; that is, the same dislocation density [19,20,24,25]. Thus, in addition to plastic strain induced by reversely mobile dislocations at the early stage of reverse loading, subsequent plastic straining up to the same dislocation density as reached
previously would presumably not aggravate the material damage for ductile cracking.

In order to estimate the evolution of material damage on the basis of the assumed ‘effective damage concept,’ the evolution of long-range internal stress should be quantitatively modeled in the FE-method. In consideration of the mechanical aspect of the Bauschinger effect, a nonlinear isotropic/kinematic (combined) hardening model was employed as a material model in FE-analysis. The pressure-independent Mises yield condition in this combined hardening model is expressed by Eq. (1)

\[
f(\sigma_{ij} - \alpha_{ij}) = \sigma(\varepsilon_p)
\]

where \(\sigma_{ij}\) is the stress tensor, and \(\alpha_{ij}\) is the back stress tensor. Moreover, the nonlinear kinematic hardening evolution law, which consists of a purely kinematic term in accordance with the linear Ziegler hardening law and a relaxation term, is expressed by Eq. (2)

\[
d\alpha_{ij} = \frac{C}{\sigma}(\sigma_{ij} - \alpha_{ij})d\varepsilon_p - \gamma \alpha_{ij} d\varepsilon_p
\]

where \(C\) and \(\gamma\) are material constants.

Namely, in this kinematic hardening material FE-model, the material damage for ductile cracking under cyclic loading can be assumed to be controlled by evolution of long-range internal stress expressed through the back stress. The effective damage concept served as the basis for proposing the ‘advanced two-parameter criterion’ for evaluation of ductile crack initiation for cyclically strained steel structures from the small-scale specimens. This criterion includes the following main ideas as shown in Fig. 6: (1) applied plastic strain, where the back stress exceeds the maximum back stress under the preceding loading cycle, does not affect the material damage—only the effective plastic strain \((\varepsilon_p)_{\text{eff}}\) at each cycle contributes to the damage, (2) ductile cracking occurs when the accumulation of \((\varepsilon_p)_{\text{eff}}\) as a function of \(\sigma_{\text{eff}}/\sigma\) during cyclic loading reaches the two-parameter critical condition obtained with monotonic loading tests and FE-analysis for the steel of interest.

This advanced two-parameter criterion associated with proposed effective damage concept would be applicable to ductile cracking estimation of structural members if the dominant mechanism for ductile cracking is nucleation of micro-voids after large-scale plastic straining.

4. Applicability of advanced two-parameter criterion based on the effective damage concept

4.1. Ductile crack initiation behavior of structural members under cyclic loading

In order to clarify the ductile crack initiation behavior from the inside and from the surface of stress/strain concentration region of the structural member under large-scale cyclic loading, two types of specimens were used. The first specimen, shown in Fig. 7, is a round-bar specimen with a shallow, blunt circumferential notch (depth = 1 mm, radius of curvature \(R = 10\) mm) subjected to cyclic, axial tensile-to-compressive loading. The second specimen, shown in Fig. 8, is a 3-point bending cross-shaped specimen with curvature \(R = 2\) mm at every corner. This cross-shaped specimen was employed so as to enable observation and discussion of the crack initiation behavior in the case where primary straining is applied in the tensile and compressive directions at the same time. The cyclic loading tests for these specimens were carried out at room temperature on a 250 kN universal tension-compression machine under displacement control conditions. During the testing, load \(P\) and...
displacement of crosshead $D$ were measured by an extensometer and recorded in a computer. Moreover, changes in the minimum diameter of the necked region for the round-bar specimen and crack initiation behavior for cross-shaped specimen were observed and recorded by a digital microscope of 25 magnifications.

Fig. 9 shows one example of the cyclic loaded test results for the round-bar specimen. Ductile cracking exhibited behavior similar to that observed in specimens under single tension. Ductile cracking associated with the nucleation and coalescence of micro-voids occurred from the specimen center before final ductile failure, when rapid reduction of load $P$ was observed.

Fig. 10 shows the deformation behaviors on the surface near the root of corner 1 and the root of corner 3 in the cyclic bended cross-shaped specimens until ductile cracking. With progress in incremental cyclic loading, asperities appeared on the surfaces of the roots of corners as shown in the micrographs at loading level (d). This is due to heterogeneous tensile straining and buckling by local compressive straining on the surface. SEM micrographs of the section at the mid-thickness have shown that the subsequent tensile straining would not deepen, but would widen the concavity. These deformation behaviors indicate that the asperities would not serve as an additional stress/strain concentrator that would influence ductile cracking. The ductile crack nucleates from the surface of the bottom of the concavity in association with nucleation and coalescence of micro-voids along the local shear band.

4.2. Applicability of the proposed criterion to estimate ductile cracking

The advance two-parameter criterion using effective plastic strain was applied to the estimation of ductile cracking for the round-bar specimens and the cross-shaped specimens under large-scale cyclic loading by conducting FE-analysis. The models are identical in size and shape with those used in the experiments. In the FE-model for round-bar specimen R10, two-dimensional axi-symmetrical elements were employed. Elements used in the cross-shaped 3D-model were 8-node isoparametric elements with 8 Gaussian points. The FE-analysis was conducted by use of the nonlinear FE-codes, ABAQUS Ver. 5.8. The combined hardening material model; that is, the stress–strain curve shown in Fig. 11, was determined from the tensile flow curves for virgin and compressively prestrained steels [18].

![Fig. 9. Result of cyclic loading test in axial direction for R10 round-bar specimen.](image9)

![Fig. 10. Ductile crack initiation behavior near the root of the corners in cross-shaped specimens under cyclic bending.](image10)

![Fig. 11. Nonlinear isotropic and kinematic hardening component used for cyclic loading FE-analysis.](image11)
Fig. 12 demonstrates the high accuracy of this material hardening model, which provides the precise deformation and local stress/strain behavior of the specimen—the true stress-true strain curve for R10 specimen obtained with combined hardening model is highly consistent with the experimental result.

On the basis of the proposed damage concept and the FE-analytical results, the cumulative history of effective equivalent plastic strain \( (\varepsilon_p^\text{eff}) \) during cyclic loading was estimated as a function of stress triaxiality \( \sigma_{tr}/\sigma \) on the crack initiation point; that is, the center of the minimum cross-section for round-bar specimens R10 and the surface of the root of corner for the cross-shaped specimens.

Fig. 13 gives an example of the estimation of effective plastic strain \( (\varepsilon_p^\text{eff}) \) obtained from the analyzed evolution of effective back stress \( \bar{\sigma} \), and cumulative history of \( (\varepsilon_p^\text{eff}) \) as a function of \( \sigma_{tr}/\sigma \) until ductile cracking in R10 specimens. The accumulated \( (\varepsilon_p^\text{eff}) \) relation at crack initiation is almost on the critical curve for ductile cracking from the specimen center obtained with single tensile specimens presented in Fig. 5. The critical applied strain \( (\varepsilon_{\text{ave}}) \) at which the cumulative history with and without considering the effective damage concept reaches the two-parameter critical condition obtained with monotonic tensile specimens was compared with experimental results. As shown in Fig. 14, along with the estimated results based on the effective damage concept for tensile specimens with single compressive and tensile prestrain tested by the authors [18], all results predicted according to the proposed criterion show close agreement with experimental results.

In the same way, as shown in Fig. 15, the cumulative history of \( (\varepsilon_p^\text{eff}) \) relation until ductile cracking for cross-shaped specimens was estimated and compared with cross-section for round-bar specimens R10 and the surface of the root of corner for the cross-shaped specimens.
the two-parameter critical condition. The accumulated \( (\hat{\epsilon}_p)_{\text{eff}} = \sigma_{p0}/\dot{\sigma} \) relation at crack initiation, which is defined when a ductile crack of about 0.05 mm length is observed, is almost the same as the critical level for single tensile specimens with ductile cracking from the specimen surface. As shown in Fig. 16, the critical load point displacement \( D \) in loading cycles predicted under constant effective plastic strain condition shows close agreement with experimental results in loading cycle and displacement level, and those predicted from the total plastic strain without considering the non-effective damage strain generally underestimate critical levels.

5. Conclusions

The damage concept, namely, that the evolution of dislocation density near the particles in steel of interest corresponds to the evolution of material damage for ductile cracking, was derived from the experimental result that ductile cracking is controlled mostly by the nucleation of micro-voids near the Ferrite–Pearlite interface of the employed steel. Moreover, in the case where large-scale cyclic loading is applied, evolution of damage was assumed to be influenced only by plastic strain other than that produced within the strain range where long-range internal stress is lower than the maximum internal stress under preceding loading. On the basis of this 'effective damage concept,' the advanced two-parameter criterion for ductile cracking for the evaluation of steel structures under large-scale cyclic loading is proposed, and employs effective plastic strain and stress triaxiality. Ductile cracking occurs when the cumulative effective plastic strain as a function of stress triaxiality during cyclic loading reaches the two-parameter critical condition obtained with monotonic loading test specimens. The effective damage strain under cyclic loading was estimated by means of FE-analysis employing a combined hardening material model by assuming that the long-range internal stress would be correlated with back stress in the hardening model. On the basis of the proposed criterion, ductile cracking from the center and from the surface of specimens subjected to cyclic loading was predicted with high accuracy. These results indicate that the advanced two-parameter criterion using the effective plastic strain derived from the combined hardening FE-material model would be a transferable criterion for evaluation of ductile cracking from both the inside and the surface of structural members subjected to monotonic and large-scale cyclic loading.

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