Damage accumulation in cyclically stable steel under low-cycle loading

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Abstract. The contribution of variable plastic strains (hysteresis loop), unilaterally accumulated plastic and elastic strains in the total accumulated damage in the limiting case (macro-crack formation) under quasi-static fracture is shown on the basis of the deformation-kinetic criterion of fatigue failure of cyclically stable steel, when the accumulated plastic strain is equal to or commensurable with the strain of a single (static) fracture. It is shown that in the case of low-cycle failure, the main damaging fraction is introduced by the static component (unilaterally accumulated strain), the value of which decreases with the increase of the number of cycles to failure (reduced load amplitude). This increases the contribution of variable cyclic strain. The influence of elastic strain in the area of quasi-static fracture is negligible, and the calculation of durability in practical applications can be carried out without taking into account the damaging role of elastic strains.

Depending on the structural state, structural metal materials can either be strengthened (the width of the hysteresis loop decreases with increasing number of loading cycles), or softened (the width of the hysteresis loop increases, consequently), or remain stable for a large share of durability under low-cycle loading with a given load amplitude (soft loading).

Steel 22k is a cyclically stable material, but under quasi-static fracture conditions (fracture strains are comparable to single-failure strains under tension). The experimental study of steel 22k under cyclic elastic-plastic deformation (low-cycle loading) was carried out under tension-compression of cylindrical samples with a diameter of 10 mm with a constant amplitude of the load with the measurement of transverse strains, which were then converted into longitudinal strains through longitudinal strain coefficients equal to 0.5 and 0.3 for plastic strains.

Steel 22k under tests at room temperatures manifests itself as a cyclically stable material (a large proportion of the durability of the hysteresis loop width remains virtually unchanged except for the initial stage), when there is hardening of the material (the width of the loop decreases the first cycles (not more than 10% of the total durability)) and in the final stage (accelerated destruction stage), when the width of the hysteresis loop continuously increases (figure 1,a).

It should be noted that all structural metal materials in the state of delivery at the initial stage are strengthened, and at the final stage-are softened.

In the area of low-cycle fatigue with a symmetrical cycle, loads are prone to unilateral (towards stretching) accumulation of plastic strains. For steel 22k character of accumulation of strains is shown in figure 1,b.

When the amplitude of the load equals to 656.6 MPa ($N_f = 8$ cycles), the material proclives, goes directly to the area of ultimate fracture with the active accumulation of plastic strains and ductility at failure is almost equal to the level of plasticity at a single (static) fracture. For conditional stresses (stresses usually attributed to the original value of the section at all stages of loading) $\sigma_a = 539$ MPa (sample 62) and $\sigma_a = 485$ MPa (sample 63) observed areas with constant levels of strains in a cycle,
passing on the final stage in an accelerated disclosure of the width of the hysteresis loop and unilateral accumulation of strains.

For the sample, which collapsed on the eighth loading cycle, there was a certain feature associated with the fact that in the first cycle the maximum cyclic strains (% \( \varepsilon \)) accumulated, then its level decreased to the value of \( \% \) and only in the last cycles the plastic strains began to accumulate unilaterally (figure 1,b).

Figure 1, a. the Curve of plastic strains in the cycles of 22k steel samples at stress amplitudes \( \sigma_a = 656.6 \text{ MPa} (\square) \), \( \sigma_a = 539 \text{ MPa} (\bigodot) \) and \( \sigma_a = 485 \text{ MPa} (\Delta) \) under tension-compression.

Figure 1,b. Accumulation of plastic strains with increasing number of cycles loading of steel 22k at \( \sigma_a = 656.6 \text{ MPa} (\square) \), \( \sigma_a = 539 \text{ MPa} (\bigodot) \) and \( \sigma_a = 485 \text{ MPa} (\Delta) \).

The character of change (immutability) of the hysteresis loop width determines the character of damage accumulation determined in accordance with the deformation criterion in the quasi-static fracture region, when the damaging role of elastic strains can be neglected, in the form of [1]:

\[
\eta = \int_{0}^{N} \frac{\varepsilon_p^2}{\varepsilon_{st}^2} dN + \int_{0}^{N} \frac{\Delta \varepsilon}{\varepsilon} dN = \text{const} \tag{1}
\]

where \( \varepsilon_p - \) is the plastic strains in the half-cycle of tension, \( \varepsilon_{st} - \) is the strains at a single (static) fracture corresponding to the true tensile strength \( S_k \) (tear resistance), \( N - \) is the number of loading cycles, \( \Delta \varepsilon - \) is the unilaterally accumulated plastic strains in the cycle.

In the limiting case (macro-crack formation) the damage is described as:

\[
\int_{0}^{N_f} \frac{\varepsilon_p^2}{\varepsilon_{st}^2} dN + \int_{0}^{N_f} \frac{\Delta \varepsilon}{\varepsilon} dN = 1 \tag{2}
\]

where \( N_f - \) is the destroying number of cycles.

With increasing durability, the role of the elastic component increases and then the level of accumulated damage is determined as [2]:

\[
\eta = \int_{0}^{N} \frac{\varepsilon_p \varepsilon_{ep}}{\varepsilon_{st}^2} dN + \int_{0}^{N} \frac{\Delta \varepsilon}{\varepsilon_{st}} dN \tag{3}
\]

and the limit state can be calculated as:

\[
\int_{0}^{N_f} \frac{\varepsilon_p \varepsilon_{ep}}{\varepsilon_{st}^2} dN + \int_{0}^{N_f} \frac{\Delta \varepsilon}{\varepsilon_{st}} dN = 1 \tag{4}
\]

where \( \varepsilon_{ep} - \) is the elastic-plastic strains in the cycle.

Figure 2 shows the increase in the level of accumulated damage, calculated according to the dependence (1), with an increase in the number of loading cycles at different amplitudes of the load (conditional stresses). Calculation of damages on experimental data was carried out in the form of:
\[ \eta = \sum_{0}^{N} \frac{\varepsilon^2_p}{\varepsilon^2_{st}} + \sum_{0}^{N} \Delta \varepsilon \varepsilon_{st} \],

and in the extreme case, as

\[ \sum_{0}^{N} \frac{\varepsilon^2_p}{\varepsilon^2_{st}} + \sum_{0}^{N} \Delta \varepsilon \varepsilon_{st} = 1. \]

Figure 2 shows the maximum accumulated damage calculated from the dependence (2).

Similarly, the damage calculation was carried out for dependencies (3) and (4).

The damaging role of elastic strains in dependencies (3) and (4) is reflected as the third term.

The calculation of the contribution of each component in the cycle is presented for the durability equal to 8 cycles is presented on figure 3,a, and the total damage of all the components in each cycle is presented on figure 3,b.

It can be seen that the main share of damage (both in the cycle and in the sum) is represented by damage from unilaterally accumulated plastic strain and to a lesser extent – from variable plastic strain (hysteresis loop width). The damaging contribution of the elastic component (figure 3,a and 3,b) is negligible and almost equal to the calculated dependences (1) and (2) to be presented on figures 1,a and 1,b.

With increasing durability (load reduction) up to 16 cycles \((\sigma_a = 539 \text{ MPa})\), the nature of the distribution of damage components practically does not change in each cycle (figure 4,a), and in the total damage for each cycle (figure 4,b), and the main contribution to the damage is made by unilaterally accumulated strains.

Further reduction of the load \((\sigma_a = 485 \text{ MPa}, N_f = 160 \text{ cycles})\) increases the contribution of repeated plastic strains (hysteresis loop width) and reduces the damaging role of single-column accumulated strains (see figure 5,a,b).

As follows from figure 5,a, in the specified range of durations (quasi-static destruction) for the durations of 8 and 16 cycles, the destruction is determined by unilaterally accumulated strains (figure 6,a). Increasing the durability to 160 cycles increases the contribution of variable plastic strains, reducing the proportion of damage from accumulated strains. At the same time and at durability of 160 cycles the main damage remains from unilaterally accumulated strains (figure 6,b).

The marked feature of the development of strains during the first cycles has changed the nature of damage accumulation of the accumulated strains when the accumulated strain in the first cycle starts
to decrease and stabilized in the second cycle. The third cycle means the beginning of the rhythmic unilateral accumulation of strains, reaching almost strains (plasticity) of a single static fracture.

Figure 3. Damage accumulation in each cycle from the individual components (a) and total in each cycle from three components. (b) from the elastic component (□), plastic (σ) unilaterally accumulated (Δ) and the total damage in the cycle of each component (●) for $\sigma_a = 656.6 \text{ MPa}$, $N_f = 8$ cycles.

Figure 4. Damage accumulation in each cycle from the individual components (a) and total in each cycle from three components. (b) from the elastic component (□), plastic (σ) unilaterally accumulated (Δ) and the total damage in the cycle of each component (●) for $\sigma_a = 539 \text{ MPa}$, $N_f = 16$ cycles.

Figure 5. Damage accumulation in each cycle from the individual components (a) and total in each cycle from three components. (b) from the elastic component (□), plastic (σ) unilaterally accumulated (Δ) and the total damage in the cycle of each component (●) for $\sigma_a = 485 \text{ MPa}$, $N_f = 160$ cycles.
This circumstance, apparently, can be explained by the fact that 22k steel is prone to intense deformation aging and, hardening in the first (initial) cycle, increases the deformation resistance in the compression half-cycle. The subsequent loading stabilizes the deformation aging process and the deformation process develops in the standard mode.

Figure 6. The total accumulation of damage from variable plastic strains (a) and unilaterally accumulated (b) for steel 22k and at stresses $\sigma_a = 539$ MPa ($\sigma$), $\sigma_a = 485$ MPa ($\Delta$) and $\sigma_a = 656.6$ MPa (□).

As it follows from the presented experimental data, in the field of quasi-static type of fracture, damage from the elastic component can be considered negligible (figure 7), the calculation of durability in practical applications can be made according to the dependencies (1) and (2).

Figure 7. Damage accumulation from the elastic component of strains for 22k steel.

Figure 8. Total accumulation damage steel with 22k cyclic loading.

Summation of damages from each of the components (figure 8) showed that the presented criteria are valid for assessing the levels of accumulated damages in the cyclic elastic-plastic deformation of steel 22k under quasi-static fracture.

Under rigid loading (loading with a given elastic-plastic deformation span), the second term in equations (1) – (6) is zero (strains accumulation do not occur).

Thus, the damage calculation showed that in the region of a small number of cycles to failure (quasi-static failure), the main damaging component is a one-way accumulated strains. With
increasing durability, the elastic component begins to play a significant role in the accumulation of damage, and in the transition region (between low-cycle and high-cycle fatigue) it becomes comparable to damage from plastic strains, and with high-cycle fatigue, elastic strains become the main (prevailing).

Unlike cyclically hardening materials (States) [2] and softening materials [1], the rate of damage accumulation with increasing number of loading cycles is more stable and most preferable for structural applications. Structural instability of the material can significantly change their plastic properties under the influence of cyclic loading and conditions for assessing accumulated damage [3].

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