Characteristic of Charpy Absorbed Energy for Steel Bridge Member with Fire Damage*

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The influence of specimen size of Charpy impact test on the absorbed energy characteristic was investigated for evaluating the toughness of steel obtained from the actual bridge member with fire damage. V-notch Charpy specimens with different thickness were extracted from the steel applied a thermal cycle simulating fire. Charpy impact test was carried out on the specimens with considering the concept of transition temperature shift proposed. The thickness effect on the Charpy absorbed energy per unit area was diminished for the steel without the fire damage by using transition temperature shift concept. On the other hand, the absorbed energy per unit area for 5 mm thickness sub-size specimen with the fire damage was higher than that for full-size specimen, even though the test temperature was shifted. The results indicated that the degree of shift temperature was different between the steels with and without the fire damage.

Key Words: Bridge, Fire, Toughness, Charpy impact test, Absorbed energy, Sub-size specimen

1. Introduction

Traffic accidents of tank trucks and misfires during bridge maintenance works etc. cause fire of bridge1~3). In any case, rapid recovering the bridges with fire damages is required for ensuring the traffic and material flow.

For recovering the bridges with fire damages, several survey and inspection are performed to identify the types and degrees of damages and to investigate the necessity and possibility of repair. For example, deformation of girder, relaxation of bolts, performance of bearings etc. are investigated4). On the other hand, the fire of bridge affects the mechanical properties of steel used for bridge member. Yield stress and ultimate strength of the steel change by thermal cycle due to fire and quench. In the same way, toughness of the steel often deteriorates by the thermal cycle. Therefore, the influence of fire on the structural performance of bridge should be clarified before recovering. For examining the influence of fire on the material properties of steel used in the bridge, material coupon test specimens are extracted from the bridge member5). In this case, the full-size specimens specified by several standards cannot be extracted from damaged bridge member because of size limitation. This limitation of specimen extraction forces us to use sub-size specimens. When using the sub-size specimens, the test results obtained by the sub-size specimens should be treated properly.

In this study, the influence of specimen size of Charpy impact test on the absorbed energy characteristic was investigated for evaluating the toughness of steel obtained from the actual bridge member with fire damage. Thermal cycle simulating fire and quench was applied on the steel5). For confirming the influence of thermal cycle on metal structures, Vickers hardness and mechanical properties of the steel were investigated. Then, V-notch Charpy specimens with different thickness were extracted from the steel. O. L. Towers and K. Wallin et al. reported the size effect on Charpy impact test result6), 7). Charpy impact test was carried out on the specimens with considering the concept of transition temperature shift proposed by K. Wallin7). Applicability of this concept on the steel with fire damage was examined from the test results.

2. Material

The material used in this study was extracted from an actual steel bridge girder constructed in 1967. The steel grade was SM41B corresponding to present SM400B. The thickness of member was reduced from the original thickness of 22 mm by corrosion. For extracting the steel with uniform thickness, the thickness of steel was reduced to 16 mm from both the upper and lower surfaces. Table 1 shows the chemical compositions and the mechanical properties of the steel at room temperature.

| Table 1  | Chemical compositions and mechanical properties |
|----------|-----------------------------------------------|
| Chemical compositions (Mass %) |
| C  | 0.181 |
| Si | 0.031 |
| Mn | 0.929 |
| P  | 0.013 |
| S  | 0.016 |
| Mechanical properties |
| Yield stress (MPa) | 291 |
| Tensile strength (MPa) | 460 |
| Elongation (%) | 30 |

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3. Heating experiment simulating fire damage

3.1 Experimental condition

It was reported that the maximum temperature of bridge member was about 800 °C when a huge fire due to traffic accident of tank truck3). A past research assumed that the maximum temperature of bridge member with fire damage by a large truck accident reached to 900 °C3). Assuming the fire damage on steel bridge, this study heated the material up to 900 °C in a furnace. The length, width and thickness of the material are 300 mm, 200 mm and 16 mm respectively. A steel plate with the same dimensions as the material was used for temperature measurement. A hole with a diameter of 4 mm was drilled from the side to the midspan of plate. A K-type thermocouple was inserted to the hole for measuring the temperature history during the heating experiment. After keeping the material in the furnace about 60 minutes, the material was taken out from the furnace and cooled by water. The cooling process simulated the fire extinguishing work3). Temperature history during fire of bridge depends on fire conditions. Therefore, it is impossible to determine the specified temperature history during fire of bridge. However, cooling rate is one of the important information for generating metal structure of steel. In this experiment, the average cooling rate from 800 °C to 500 °C was about 4.3 °C/sec.

3.2 Experimental result

After finishing the heating experiment, the microstructures of steels were observed by an optical microscope. Fig. 1 shows the microstructures of the steels. Here, the material without heating / cooling was named steel ‘B’. The material with heating / cooling was named steel ‘F’. The microstructure of steel B was ferrite and pearlite. On the other hand, the microstructure of steel F changed to ferrite and martensite or bainite due to heating up to 900 °C and quench from it.

In order to investigate the difference of influence of heating and quench on the surface and the inside of steel, Vickers hardness test was carried out on the steels in the thickness direction. Fig. 2 shows the result of Vickers hardness test. The magnitude of load for the hardness test was 9.8 N. The difference of hardness was small between the surface and the mid-thickness of steel in both steels B and F. The hardness was almost uniform around the mid-thickness of the steels.

For examining the change of mechanical properties due to heating / cooling, the tensile test was performed. Two round bar tensile test specimens with diameter of 6 mm were extracted from each steel. The gage length of tensile test specimen was 25 mm. The elongation was measured by using a digital video camera.

Fig. 3 shows the stress-strain relationships of the steels B and F. The results of two specimens are almost the same in the steels B and F respectively. Therefore, the result of one specimen in each steel is shown in the figure. The yield stress and the ultimate strength of the steel F became higher than those of the steel B due to heating / cooling. Furthermore, the yield ratio of the steel F (YR = 0.72) became higher than that of the steel B (YR = 0.63).

It is also caused by the increase of yield stress and ultimate strength due to heating / cooling. The influence of specimen configuration on the brittle fracture toughness of structural steels is affected by work hardening properties9). For investigating the change of work hardening exponent by heating / cooling, the true stress and plastic strain relationships transformed from the nominal stress and nominal strain relationships were shown in Fig. 3 (b). The curves are drawn up to the uniform elongation before starting the necking. The approximation curves with Swift’s hardening law shown by Eq. (1) are applied. The approximation curves for each steel are described by dotted lines in Fig. 3 (b).

\[ \sigma_t = C (\alpha + \varepsilon_p)^n \]  

(1)

Where, \( \sigma_t \) is the true stress, \( C \) and \( \alpha \) are the work hardening coefficients and \( n \) is the work hardening exponent.

The work hardening exponent, \( n \) of the steel F \( (n = 0.13) \) became smaller than that of the steel B \( (n = 0.20) \) from the curve fitting results.

![Fig. 1 Microstructures of steels with and without heating / cooling](image)

![Fig. 2 Distribution of Vickers hardness in thickness direction](image)
The Charpy absorbed energy may be affected by the change of hardening properties by heating / cooling. It was reported that the change of yield ratio and work hardening exponent influenced the near-tip stress of notched steel 9). The yield ratio of the steel F became larger than that of the steel B. However, the work hardening exponent of the steel F became smaller than that of the steel B. These changes of hardening properties due to heating / cooling possibly affect the stress field around the notch of the specimens with different thicknesses.

4. Charpy impact test

4.1 V-notch Charpy specimen

V-notched Charpy specimens with different thickness were extracted from the steel B and the steel F. The thicknesses of specimens were 10 mm (full-size), 7.5 mm and 5 mm (sub-size). The width of specimen was 10 mm and the length of specimen was 55 mm. All specimens with different thickness were extracted from the section mid-thickness in order to minimize effects of material inhomogeneity.

4.2 Concept of transition temperature shift

K. Wallin proposed a shift in transition temperature $\Delta T$ (°C) for obtaining the same absorbed energy per unit area among the different specimen thicknesses 7).

$$\Delta T = 51.4 \ln (2 (B / 10)^{0.2} - 1)$$  \hspace{1cm} (2)

Where, $B$ is the specimen thickness (mm).

Based on this equation, test temperatures for obtaining the same absorbed energy of 10 mm thick specimens were -8 °C and -20 °C for 7.5 mm and 5 mm thickness specimens respectively. Therefore, the specimens with 10 mm thick were tested at 0 °C. The specimens with 7.5 mm and 5 mm thick were tested at -8 °C and -20 °C in addition to the test temperature of 0 °C. Three specimens were tested for each temperature condition by using a test apparatus of 490 J class.

4.3 Result and discussion

Fig. 4 and Fig. 5 show the Charpy absorbed energy and the crystallinity of all specimens. The average value of Charpy absorbed energy and the crystallinity at 0 °C for full-size specimen of the steel B was about 30 J and 73 %. The Charpy absorbed energy decreased and the crystallinity increased by heating / cooling. The energy of the steel F was about 50 % of that of steel B at 0 °C in the all specimen thicknesses. The average crystallinity of the steel F at 0 °C in the all specimen thicknesses became about 90 %. The same tendency was observed in the specimens with 7.5 mm thick at -8 °C. However, the Charpy absorbed energy of the specimens with 5 mm thick at -20 °C was not changed by heating / cooling. The crystallinity of the specimens with 7.5 mm thick at -8 °C and the specimens with 5 mm thick at -20 °C became slightly higher by heating / cooling.

Fig. 6 shows the Charpy absorbed energy per unit area, $\sigma E/A$ tested at 0 °C. The decreases of $E/A$ by heating / cooling varied among the different specimen thicknesses. The average $E/A$ value decreased from 0.4 to 0.2 in the specimens with 10 mm thick, from 0.4 to 0.3 in the specimens with 7.5 mm thick and from 0.6 to 0.3 in the specimens with 5 mm thick respectively. The $E/A$ increased with reducing the thickness of specimen in both of the steels B and F. This tendency can be confirmed relatively clearly in the steel B rather than in the steel F.

| Material | Yield stress, $\sigma_Y$ (MPa) | Ultimate strength, $\sigma_U$ (MPa) | Elongation, $\varepsilon_B$ (%) | Yield ratio, YR | Approximation curve: Swift’s law $\sigma = C (\varepsilon + \varepsilon_0)^n$ |
|----------|-------------------------------|----------------------------------|-----------------------------|------------------|-----------------------------------------------|
| Steel B  | 291                           | 460                             | 30                          | 0.63             | $C = 321$  \hspace{1cm} $n = 0.74$          |
| Steel F  | 440*                          | 613                             | 19                          | 0.72             | $n = 0.13$                                      |
Fig. 7 shows the comparison of the $vE/A$ considering the shift in transition temperature $\Delta T$. In the steel B, the $vE/A$ obtained by sub-size specimen at 0 °C + $\Delta T$ was close to that for full-size specimen at 0 °C. The $vE/A$ obtained by 10 mm thickness full-size specimen tested at 0 °C was relatively close to the specified energy value (33.75 J/cm²), which was the basis for the transition temperature shift concept proposed by K. Wallin⁷).

The $vE/A$ obtained by 5 mm thickness sub-size specimen at -20 °C was higher than that for full-size specimen in the steel F. The reason of this result might be as follows. The $vE/A$ obtained by 10 mm thickness full-size specimen at 0 °C was about 20 J/cm² in the steel F. That was smaller than the specified energy value for the transition temperature shift concept. Furthermore, the degree of influence of heating / cooling on the $vE/A$ was thought to be different with the specimen thickness. The decrease of $vE/A$ of the 5 mm sub-size specimen was larger than that in the 10 mm full-size specimen at 0 °C. It is possible that the change of hardening properties by heating / cooling affect the degree of decrease of $vE/A$ in the different specimen thickness⁹). The influence of the change of hardening properties by heating / cooling on the Charpy absorbed energy with different specimen thickness and the proper value of transition temperature shift for the steel with heating / cooling are investigated continuously.

5. Conclusions

The influence of specimen size of Charpy impact test on the absorbed energy was investigated for evaluating the toughness of steel extracted from the actual bridge with simulated fire damage.

The obtained main results are as follows.

1. The simulated fire damage changed the mechanical properties of steel used for the bridge member. The yield stress, the ultimate strength and the yield ratio increased by 51%, 33% and 14% from those of the steel without the fire damage respectively. The work hardening exponent of the steel with the fire damage decreased by 35% from that of the steel without the fire damage.

2. The simulated fire damage deteriorated the Charpy impact toughness of the steel. The Charpy absorbed energy per unit area ($vE/A$) increased with reducing thickness of specimen at the same temperature (0 °C) with or without the fire damage.

3. The thickness effect on the Charpy absorbed energy per unit area was diminished for the steel without the fire damage by using transition temperature shift concept.
The degree of influence of heating / cooling on the value of $V/E/A$ might vary among the different specimen thicknesses. The decrease of $V/E/A$ of the 5 mm sub-size specimen was larger than that in the 10 mm full-size specimen at 0 °C. It is possible that the change of hardening properties by heating / cooling affect the degree of decrease of $V/E/A$ in the different specimen thickness.

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