Study on Fracture Toughness Indices of Chinese Structural Steel and Weld Metal

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ABSTRACT

Brittle fractures in welded beam-to-column connections occurred at the events of the 1994 Northridge Earthquake and the 1995 Kobe Earthquake. The material fracture toughness was considered as one of the most significant factors that induced the fractures at the connections. The present work has collected a number of fracture toughness data for the commonly used structural steel and weld metal in China. Effects of temperature, pre-strain conditions and loading rates on fracture toughness are deeply analyzed. The toughness indices, such as CVN (Charpy V-Notch impact energy), \( K_{IC} \) (Critical Stress Intensity Factor) and CTOD (Crack Tip Opening Displacement) value \( \delta_m \), all decrease as the decreasing of temperature. In comparison with the non-prestrained material, fracture toughness values \( \delta_m \) of Q235 decrease by 74% and 84% at 5% and 10% pre-strain conditions respectively. The loading rates seem to have less effect on fracture toughness compared to pre-strain conditions, except for Q235 base metal. Consequently, the temperature, pre-strain conditions and loading rates should be considered in the selection of material fracture toughness. Finally, the elastic and inelastic fracture toughness values of typical Chinese structural steel and weld metal are recommended.

KEY WORDS: Fracture toughness; CVN; Stress intensity factor; CTOD; Pre-strain; Loading rate.

INTRODUCTION

The welded steel moment resistant frames (WSMFs) encountered an unexpected failure mode called brittle fracture, at the events of the 1994 Northridge Earthquake in the U. S. and the 1995 Kobe Earthquake in Japan. Post-earthquake inspections showed that many of these fractures occurred at or around the beam bottom flange to the column flange groove welds or the heat affected zone (HAZ) (Koji Azuma et al., 2000). The cracks generally initiated at various weld defects or the tips of ductile cracks which grew from geometric discontinuities (such as backing bar, welding access hole, shear tab, continuity plates in the column, etc.). The fracture toughness of the material was one of the most important factors that induced the fractures at the beam-to-column connections in welded steel moment resistant frames.

Both post-earthquake inspections and laboratory tests of full-scale connection assemblies indicated that, majority of the fractures occurred after beam flanges sustained extensive yielding and/or local buckling. Therefore, the fracture toughness of the material at pre-strain conditions should be estimated. Besides, the low temperature and dynamic loading effects on the fracture toughness should be taken into account.

As far as now, several fracture mechanics-based methodologies have been developed for evaluating the fracture behavior of the beam-to-column connections, such as probabilistic fracture mechanics model (the weibull stress model) developed by C.G. Matos et al. (2001; 2002), the computational fracture mechanics method developed by W.M. Chi (2000) and the micromechanics based stress modified critical strain (SMCS) method developed by W.M. Chi and A.M. Kanvinde et al. (2004; 2006).

However, the fracture toughness data of typical Chinese structural steel and weld metal are not sufficient and systematic. The present work has collected the data obtained from fracture toughness tests performed by Wu (2004), Zhang (2004) and Li (2002), respectively. Special emphasis is on the effects of temperature, pre-strain conditions and loading rates on the material fracture toughness. Finally, the elastic and inelastic fracture toughness values of typical Chinese structural steel and weld metal are recommended.

CORRELATION WITH FRACTURE TOUGHNESS

Fracture toughness indices

The conventional toughness index CVN (Charpy V-Notch impact energy) can represent the fracture resistant ability of materials to a certain extent. CVN is widely used as the toughness measurement of materials in steel structural engineering because of the simple and convenient impact test. While CVN data provide a qualitative check on fracture toughness, the CVN impact energy does not directly relate to fracture indices calculated by analysis. Therefore, it is necessary to correlate the CVN data to more rigorous fracture toughness indices in fracture mechanics analyses. For mode I crack, there are mainly three fracture indices as follows (Wei-Ming Chi, 2000):

- \( K_{IC} \) - Elastic stress intensity factor at plane strain conditions, it is a measurement of the critical value of stress singularity at the crack tip under predominately elastic conditions or small scale yielding conditions.
- CTOD value \( \delta_m \) - Inelastic crack tip opening displacement, whose critical value is a measurement of the maximum blunting of the crack tip (front) at the onset of crack initiation. It is applicable for elastic-plastic fracture mechanics analyses.
- \( J_{IC} \) - A ductile fracture toughness index based on the strain energy release rate associated with the crack extension. The J-integral is equal to the linear or nonlinear strain energy release...