Journal of Constructional Steel Research 134 (2017) 1–16

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Simulation of block shear fracture in bolted connections

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ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 23 February 2017
Accepted 9 March 2017
Available online xxxx

Keywords:
Steel structure
Gusset plate
Coped beam
Block shear
Bolted connection
Numerical simulation
Ductile fracture
Fracture mechanism
Fracture path
Fracture profile

ABSTRACT

Block shear failure in bolted connections is a complex failure mode in steel connections. The complexity of this failure is due to the varying stress-state conditions along the failure path. Failure under this mechanism is distinctively characterized by ductile fracture, particularly on the shear plane, which has recently been identified to not only be dependent on stress triaxiality but also on Lode parameters. Existing numerical models provide extensive knowledge on important performance parameters in the connection; however, further improvements of current simulation approaches can yield significant dividends in characterizing fracture initiation and progression until failure. The aim of this paper is to develop a new numerical simulation technique for capturing block shear failures in bolted connections and to utilize the developed models for further understanding the failure. Specifically, numerical models of gusset plate and coped beam connections are created and loaded up to and including total fracture. This is realized through the application of a newly developed ductile fracture criterion that accounts for the dependency of the fracture path on stress triaxiality and Lode angle parameter. Laboratory test results on large-scale bolted connections serve for validation of the analysis technique. Comparison between the numerical and experimental results include load versus displacement, fracture sequence, and fracture profile and an overall excellent correlation is shown. Through the numerical simulations, the intrinsic mechanisms of block shear in gusset plate and coped beam connections are discussed and the effect of various levels of beam end/rotations, for coped beam connections, on block shear failure is explored. The modeling approach presented in this study can be an alternative mean for modeling block shear failure and can be extended to other types of connections. The analysis results provide insight on block shear failure mechanism and the factors dominating the behavior of this type of connection.

1. Introduction

Block shear is one of the governing failure modes for bolted connections. In a block shear failure, a block of material is partially or entirely removed from the parent component. The most significant feature of block shear is the presence of varying stress state conditions that cause the fracture to propagate on a tension and shear plane, and in some cases with additional inclined planes. The presence of these different failure paths undoubtedly will have an impact on the resulting connection characteristics including strength and ductility. Therefore, the ability to model such failure can be beneficial in understanding the true behavior of the connection. It is important to note that simulations conducted in previous studies [1,2,3], due to limitations in modeling capabilities, were unable to capture failure of the connection (i.e., no crack initiation or propagation). This is because until recently, the majority of the ductile fracture models utilized in numerical simulations were capable of capturing tension failure only. For block shear failure, the utilization of a ductile fracture model that can allow for the development of shear failure, in addition to tension failure, is required.

Although it has been extensively studied, predicting ductile fracture of metals is still a considerably challenging undertaking. There have been several profound transformations in recent decades on understanding the dependency of ductile fracture on various stress states. Specifically, dependency on the stress triaxiality was first theoretically introduced by McClintock [4] and Rice and Tracey [5] and later identified and confirmed analytically and experimentally in many studies including for example Gurson et al. [6], Johnson and Cook [7], Benzerga and Leblond [8] Wen and Mahmoud [9]. However, it was not until very recently where researchers shifted their attention to the role of Lode angle on ductile fracture, which has been confirmed and modeled in a number of studies including Xue [10], Bai and Wierzbicki [11], Bai and Wierzbicki [12], Wen and Mahmoud [9], Wen and Mahmoud [13]. Fig. 1 (a) shows a schematic representation of a stress vector OB on the principal stresses space and the corresponding definition of the Lode angle. Fig. 1 (b) shows the geometrical representation of the Lode angle, which is the smallest angle between the line of pure shear

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http://dx.doi.org/10.1016/j.jcsr.2017.03.006
0143-974X/

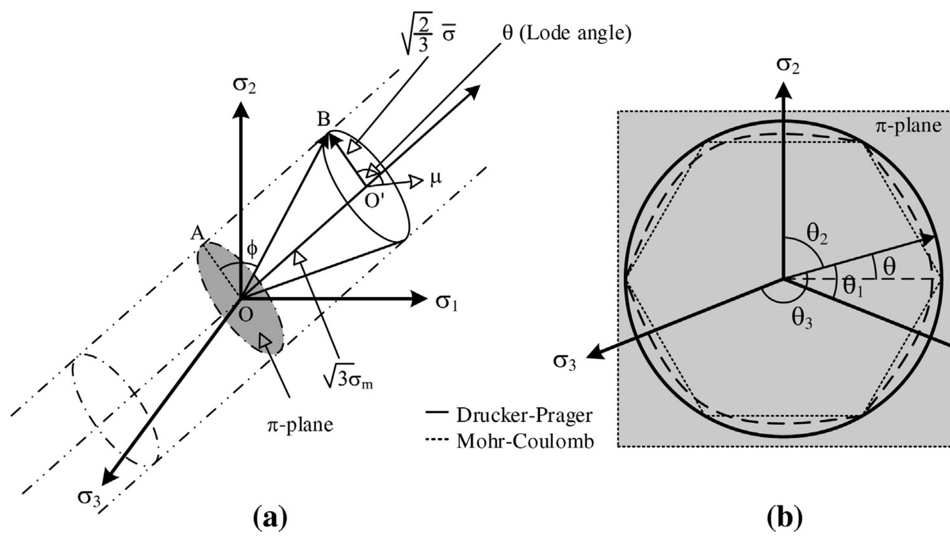

Fig. 1. (a) Schematic representation of a stress vector OB on the principal stresses space and (b) definition of the Lode angle on the π-plane. Adapted from Bai and Wierzbicki [11].

and the projection of the stress tensor on the deviatoric plane (also known as the π-plane). The π-plane is the plane on which the summation of the principal stresses is equal to zero. The triaxiality and Lode angle are often referred to the tensile and shear fracture parameters, respectively, because of the role each play on the fracture developed under the respective loading. Undoubtedly, block shear is influenced by both fracture parameters, such that both parameters need to be considered in simulating block shear failure.

Wen and Mahmoud [9] introduced a new and accurate ductile fracture model that accounts for the triaxiality and Lode parameter and comprises of minimal number of parameters to be calibrated in comparison to other models. The Wen-Mahmoud model, discussed briefly in this paper, is therefore utilized in this study for simulating block shear failure.

Most representative block shear fractures are usually associated with gusset plate and coped beam connections. In gusset plate connections, the development of block shear is due to direct tension loading on a member connected to the gusset plate. There have been many laboratory tests on gusset plate connections and accurate and reliable data were obtained from these tests including for example Huns et al. [1], Whitmore [14], Hardash and Bjorhovde [15], Bjorhovde and Chakrabarti [16], Nast et al. [17], and many others. However, tests that captured the entire fracture process up to and including failure, with focus on the fracture mechanism are relatively limited. In coped beam connections, the development of block shear is a result of predominately shear loading on the connection that could be coupled with secondary moment because of beam end rotations. Compared to gusset plate connections, the behavior of bolted coped beam connections, in the presence of beam end rotations, is featured with asymmetric stress distribution resulting from the complex loading conditions. As a result, the failure path is often also asymmetrical, and thus existing results from gusset plate tests cannot directly be extended to bolted coped beam connections. Block shear failure in coped beams was first identified by Birkemoe and Gilmor [18] through comparative testing that included one coped and one un-coped beam. It was subsequently confirmed through testing conducted by Yura et al. [19], Ricles and Yura [20], Aalberg and Larsen [21], Franchuk et al. [2], Fang et al. [22], and Lam et al. [23].

Due to the high cost and space and equipment limitations associated with full-scale tests, numerical simulation can serve as a substitute or supplement to testing and can provide meaningful insight on complex phenomena. Numerical simulation on connections, pertaining to block shear, evolved from the two-dimensional linear elastic and nonlinear finite element models (Huns et al. [1]; Ricles and Yura, [20]; Franchuk et al. [2]) to three-dimensional solid element nonlinear models (Yam et al. [24]; Wei et al. [25]; Yam et al. [26]; Fang et al. [22]). Previous studies provided viable predictions of connection behavior in some cases but not in other cases. This is because limitations in modeling capabilities did not allow for the development and propagation of failure, particularly on the shear plane, which is essential to include for reliable predictions of connection capacity and ductility.

In this paper, numerical simulations of block shear in gusset plate and coped beam connections are conducted up to and including total failure, through the application of a newly developed ductile fracture criterion with consideration of both the stress triaxiality and Lode angle parameter. The laboratory test results from Huns et al. [1] and Franchuk et al. [2] are utilized for validation of the numerical modeling approach and for comparing the outcome of the numerical study to real experimental data and observations. The comparisons include load verses displacement curves, fracture sequence, and fracture profile. Through the numerical simulations, the inherent mechanisms of block shear in gusset plate and coped beam connections are thoroughly discussed including the effect of various levels of beam end rotations on connection behavior.

2. The fracture criterion

One of the predominate features of block shear failure is the presence of the tensile and shear fractures, which are dependent on stress triaxiality and Lode parameter, respectively. However, most of existing and widely used ductile fracture models such as the Rice-Tracey model [5] and Johnson-Cook model [7] are only dependent on stress triaxiality as shown in Eqs. (1) and (2), respectively. Fracture models that are solely dependent on Lode parameter are also available, such as the well-known maximum shear criterion or Tresca criteria, shown in Eq. (3).

$$\overline{\varepsilon}_f = c_1 \exp(c_2\eta) \tag{1}$$

$$\overline{\varepsilon}_f = c_3 \exp(c_4\eta) + c_5 \tag{2}$$

$$\overline{\varepsilon}_f = c_6\left[\cos\left(\frac{\pi}{6}\overline{\theta}\right)\right]^{c_7} \tag{3}$$

where $\overline{\varepsilon}_f$ is the fracture plastic strain, c_1 to c_7 are material constants, η and $\overline{\theta}$ are the stress triaxiality and Lode angle parameter, respectively,