Numerical study of block shear limit state in welded gusset plates

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ABSTRACT

The block shear failure is a common limit state that governs the base metal strength in welded connections. The framework for block shear strength prediction adopted by current design specifications is originally based on research results on bolted joints. Also, in the past few studies conducted on welded connections, the mechanical properties of the steel used are distinct from the commonly applied steel in Iran. In this paper, first, a nonlinear finite element model with ductile damage capability was developed and validated against available test results on welded gusset plate connections. Then, a parametric study was performed on connection length, connection width, welding configuration, and gusset plate thickness, in which, the strain and stress distribution, as well as the block shear rupture path, were investigated. The results showed that the mechanics of block shear failure in welded connections is different from bolted ones for reasons like stress triaxiality development in tensile failure plane due to the existence of additional constraint against necking of base metal fibers adjacent to the weld. Evaluation of existing block shear strength equations revealed that the AISC block shear design equations provide so conservative capacities, on average 36%, for welded connections. Accordingly, a new block shear strength equation was developed, such that, the predicted nominal block shear strengths are on average about 5% on the conservative side, however, using the LRFD load and resistance factors in the design along with this equation, the safety needed for this limit state is ensured.

KEYWORDS

Block shear; gusset plate; welded connection; base metal strength; finite element analysis.

Introduction

Block shear failure is one of the probable failure modes for welded structural steel connections in which a block of base metal material surrounding the welded region is detached from the connecting element. The most remarkable feature of this failure mode is a variable contribution of two stress components: tensile stresses in the planes perpendicular to the loading direction and shear stresses in the planes parallel to the loading direction. The ANSI/AISC 360-16 specification [1] suggests the block shear nominal strength, R_n, as the lesser of the following two equations:

$$R_n = 0.6F_u A_{nv} + U_{bs} F_u A_{nt} \quad (1)$$

$$R_n = 0.6F_y A_{gv} + U_{bs} F_u A_{nt} \quad (2)$$

where F_y and F_u are the yield and tensile strengths of the steel material, respectively, A_{nv} and A_{gv} are the net and gross areas subjected to shear, respectively, A_{nt} is the net area subjected to tension and U_{bs} is a reduction coefficient for nonuniform tensile stresses. It should be noted that in welded connections, the gross and net areas are identical; hence, Eq. (2) always governs and also $U_{bs} = 1$. The block shear design strength equation in current North American design standards has been mainly based on research results of steel members with bolted connections and later were extended to encompass welded connections. The structural behavior and the block shear capacity of gusset plates with bolted end connections have been studied by a number of researchers [2-4]. However, for welded connections, research studies are scarce [5]. Topkaya [6] investigated the BS failure in welded gusset plates through experimental and numerical studies. It was shown that the mechanics of block shear failure in such connections is different from bolted connections. Oosterhof and Driver [7] conducted numerical and experimental research on BS failure in concentrically loaded welded lap plate connections.

This paper discusses the numerical study that have been carried out to investigate the block shear strength of welded gusset plates. Once validated by comparison with the available test data, nonlinear finite element (FE) model was employed to conduct a parametric study in order to examine the effects of various parameters such as connection geometry and weld arrangement on the block shear strength of welded gusset plates. Finally, as the main objective of this research, a new block shear strength prediction equation was proposed.

Methodology

The general purpose finite element (FE) software ABAQUS [8] was used to simulate the models of welded gusset plate connections shown in Figure 1. The FE models are assembled from three parts: lap plates, gusset plate, and welds. Two types of welding arrangement are considered. Weld group type (A) has only longitudinal welds, while weld group type (B) has both longitudinal and transverse welds. The three dimensional element (C3D8R) is used to mesh all components of the model. Stress-strain data were taken from the result of the coupon test of S235 steel [9]. The von Mises yield criterion and its associated flow rule was used to detect the onset of plastic deformation in the gusset plate. In order to input the data into ABAQUS, the engineering stress-strain data were converted to true stress and strain values. To obtain an accurate failure pattern, the "Damage for Ductile Metals" module available in ABAQUS was utilized to consider material strength degradation due to initiation and evolution of cracks. The FE modeling assumptions described above were validated through simulation of the available test data. Table 1 indicates a summary of the geometric parameters involved (as defined in Figure. 1), for twenty welded gusset plate connections.

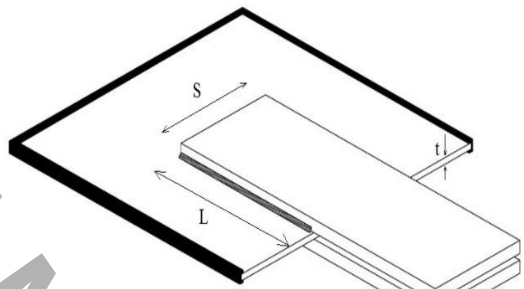

Figure 1. A typical welded lap plate connection

Table 1. Models properties

Model #	Type	*L* (mm)	*S* (mm)	*t* (mm)
1	A	100	100	4
2	A	75	100	4
3	A	50	75	4
4	A	125	100	4
5	A	100	75	4
6	A	100	100	5
7	A	75	100	5
8	A	50	75	5
9	A	125	100	5
10	A	100	75	5
11	A	100	100	6
12	A	75	100	6
13	A	50	75	6
14	A	125	100	6
15	A	100	75	6
16	B	100	100	4
17	B	75	100	4
18	B	50	75	4
19	B	125	100	4
20	B	100	75	4

Results and discussion

The data gathered from the FE analyses showed that all models were failed in block shear with a U-shaped failure path including a tensile plane and two shear planes. Figures 2 and 3 illustrate and von Mises and PEEQ contours at the ultimate capacity level for model #1. Block shear fracture is initiated from the critical zone located at the corners of tensile plane and then is propagated to shear rupture in shear planes.

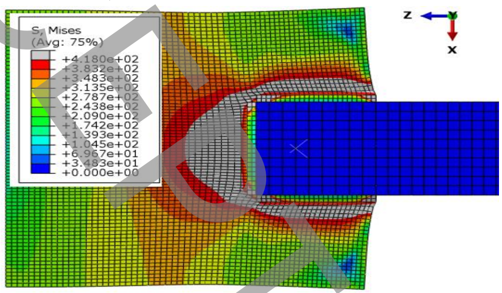

Figure 2. Von Mises stress contours at the ultimate

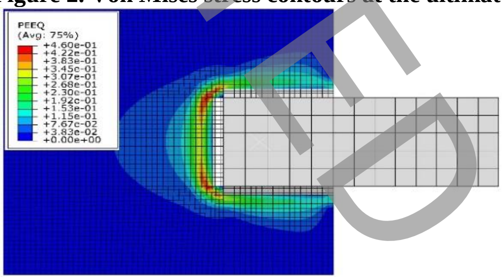

Figure 3. PEEQ contours at the ultimate load

The tensile and shear stress distribution along the failure planes at the ultimate strength for models #1 and #16 are shown in Figures 4 and 5, respectively. As seen in the figures, the tensile and shear stresses distribute on the failure planes uniformly, except for the edges where stress concentration exists. The average shear stress on the shear plane is about $0.6F_u$, and the average tensile stress on the tensile plane is about 20% higher than F_u due to stress triaxiality presence. Also, comparing the results of models #1 and #16 shows that transverse weld presence has no significant influence on stress distribution as well as, the block shear capacity as shown in Figure 6.

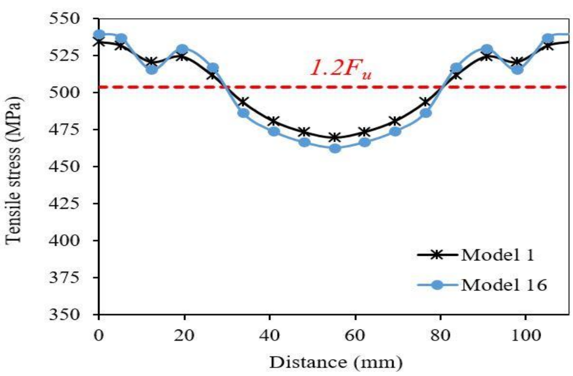

Figure 4. Tensile stress distribution in models #1 and #16

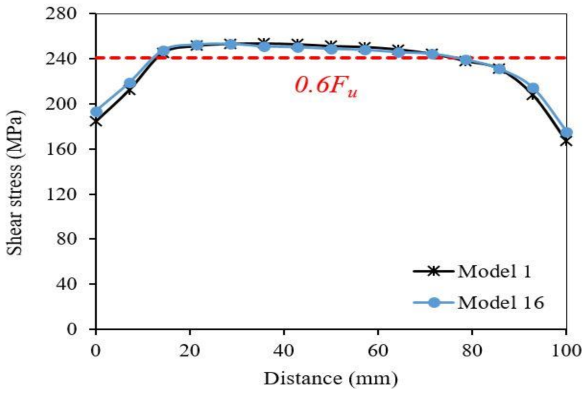

Figure 5. Tensile stress distribution in models #1 and #16

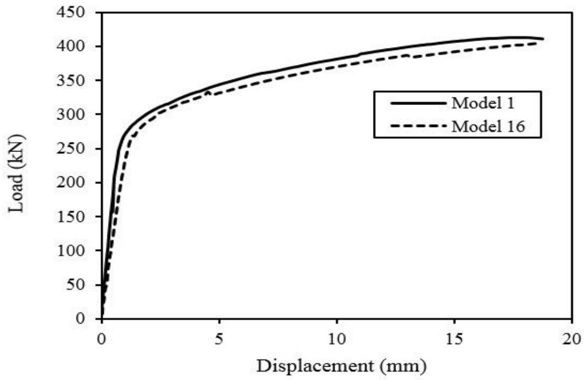

Figure 6. Load-displacement response in models #1 and #16

The results showed that the stress triaxiality presence in the tensile failure plane makes the block shear failure mechanism in welded plates different from those in bolted ones. Indeed, fibers of the base metal in the net tensile failure plane of bolted connections can freely endure necking both in the direction of the plate thickness as well as, in the perpendicular direction to the loading, while in welded connections, necking is allowed only in the thru thickness direction. Considering these phenomenological aspects, the nominal block shear design equation of a welded gusset plate under a single component concentric loading is proposed in Eq. (3). The new equation provides more accurate estimation of block shear strength, especially for the structural steel which is common in Iran.

$$R_n = 1.2F_u A_{nt} + 0.6F_u A_{gv} \tag{3}$$

Conclusion

- The block shear failure mechanism in welded gusset plates differs from those in bolted ones for reasons like the presence of stress triaxiality in the tensile plane, and equality of net and gross areas of shear planes.
- The average shear stress on the shear plane is about $0.6F_u$, and the average tensile stress on the tensile plane is about 20% higher than F_u due to stress triaxiality presence.

- Considering these phenomenological aspects, a new nominal block shear design equation of welded gusset plates under a single component concentric loading is proposed which provides a more accurate estimation of block shear strength, especially for the structural steel which is common in Iran.

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