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Experimental and numerical study of frictional effects on block shear fracture of steel gusset plates with bolted connections

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A B S T R A C T

In this paper, an experimental and a numerical study has been conducted to get information about the effects of slip-critical connections in gusset plates of bolted steel tensile members. To this end, a total of 28 double gusset plates were subjected to tensile loading in seven groups, while the parameters such as the properties of specimen materials, number of bolts, amount of frictional coefficient and the type of connections were selected as experimental variables. A 3D non-linear finite element analysis was done to determine the distribution of tension and shear stresses at different times of tensile loading, showing good agreements with the results of the experiment. The results of the experimental tests and the finite element analysis showed that frictional force due to a pre-tightening force of slip-critical connections could have a significant effect on the capacity response and fracture behaviour of gusset plates under tensile loading with block shear fracture. Therefore, increasing frictional coefficient, reduction of thickness, and the resistance of specimen materials, increased the effect of frictional force on them. On the other hand, in order to evaluate the proposed equations of AISC 2016 and CSA2009 standards, as well as the proposed equations of Topkaya, C. (2004) [13] and Teh and Uz (2015) [14], for predicting the strength of block shear fracture, a comparison was done between the strengths obtained from the predictions of their equations and the strength obtained from laboratory tests. With this comparison, it was found that AISC 2016 and CSA2009 standards have the most conservative and non-conservative forecasts in the proposed equations. In addition, by changing the effective shear stress in the proposed equation of Teh and Uz (2015), from the value of $0.6F_u$ to $\frac{F_u}{\sqrt{3}}$, more precise predictions are provided in comparison to other equations studied in this paper, in which the main reason for its precision is better observation of the shear contribution, because this equation uses active shear planes instead of net or gross shear planes.

1. Introduction

Bolted connections are categorized into two groups: bearing-type and slip-critical type connections. A bearing-type connection is used when a partial slip is allowed between gusset plates; otherwise, a slip-critical connection is applied. In a bearing-type connection, the mechanism of load transfer between gusset plates of members under axial tensile force is based on the contact of the bolt body with a hole wall. Therefore, shear stress is created in a bolt and compressive stress is created in the wall of the hole and the bolt. In addition, in a slip-critical connection, the load transfer between gusset plates is based on frictional force resulting from pre-tightening of bolts.

Different failure mechanisms in bolted connections and parts will be studied in bearing and slip-critical connections. One of the failure mechanisms of connections under a tensile load is a block-shear fracture. This occurs in steel elements resulting from the simultaneous effects of tension and shear stresses, which rupture a part of the element [1]. Therefore, the block-shear capacity of an element is lower than its ultimate strength. In simultaneous tension and shear stresses, tension stress occurs in part of an element, while shear stress occurs in another part, such that the tensile plane is formed perpendicular to the loading direction and shear plane is created in the direction of loading. This is more common in bolted than welded connections because of a reduction in the section area of the element due to the presence of bolt holes.

In the design standard of AISC-2016 [2], block shear fracture has been identified as the limit in the determination of resistance of bolted connections and in states of failure fracture of tensile planes, yield or shear fractures are possible [3–6]. Based on such standards, the relation of block shear is as follows:

$$P_u = 0.6F_uA_{nv} + U_{bs}F_uA_{nt} \le 0.6F_yA_{gv} + U_{bs}F_uA_{nt} \quad (1)$$

where A_{nt} is the net area subject to tension, A_{nv} = net area subject to shear, A_{gv} = gross area subject to shear, F_y = steel yield stress, F_u =

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ultimate stress of steel, U_{bs}= the reduction factor to approximate the non-uniform stress distribution on the tensile area.

Relations of block shear fracture design in AISC-2016 specifications are based on the results of experimental studies conducted on members of coped beams [1] and gusset plates [3] and were integrated with experimental studies conducted on non-uniform tension stress distribution (U_{bs}) on tensile plane [7–9]. All experimental studies had a bearing-type connection and effort was made to remove frictional effects on experimental results.

Experimental study of coped beams' members showed that presence of frictional forces in connections could have an effect on the strength of members against block shear fractures such that connections with one bolt row are more effective than connections with the two-bolt row thus the results are conservative [10,11].

In the present research, effects of pre-tightening forces of slip-critical connections on block shear fracture of bolted steel gusset plates under tensile axial loading have been studied by experimental testes and a nonlinear finite element analysis. To this end, 28 specimens of double gusset plates were subjected to tensile loading. Material properties, the number of bolts, the amount of friction coefficient, and the type of connection have been considered as experiment variables. Results obtained by equations suggested by AISC 2016 and CSA-S16-14 [12] specifications as well as equations proposed by Topkaya [13] and Teh and Uz [14] were compared with those obtained by the experimental tests to evaluate accuracy.

2. Experimental programme and test results

2.1. Material properties

In the present research, a total of seven double gusset plates with bolted connections and three types of materials (ST37-2, ST44-2 and ST52-3) that were produced based on DIN specifications were tested via the axial tensile loading. The aforementioned materials are similar to A36, A572/42 and A572/50 in the ASTM specification. The nominal thickness was 4 mm for specimens with material type A572/42–50 and nominal thickness of 4 and 8 mm was used for specimens with material type A36. The material properties of the specimens were obtained through a coupon test based on the standard of the ASTM specification A370-2014 [15]. Three tests were made perpendicular to rolling for each material with 12 mm wide and 50 mm gauge length. The mechanical properties of specimen materials, in which the nominal thickness of the material type A36 was 4 mm, were not tested because they were used in an experimental study conducted by Samimi et al. [16]. Therefore, the results of the above study were used for materials' mechanical properties. The yield strength of the materials of the specimens was calculated by the offset method (0.2). Moreover, to obtain the true stress and strain of fracture time, the initial and ultimate cross-sectional areas were measured before the test and after the fracture of specimens, respectively. Mean amounts of yield stress F_y, ultimate stress F_u, elasticity module E, hardening strain ε_H, strain in ultimate stress ε_u, initial cross-sectional area A_I, post-fracture cross-sectional area A_F and fracture load (P_f) of specimens have been listed in Table 1.

The property class of bolts was 10.9, corresponding to that of DIN EN-14399-4 [17]. The nuts and washers were manufactured with the class of 10 according to DIN EN-14399-4, using the DIN EN-14399-6 [18] standards.

To determine the amounts of static and dynamic friction coefficients of the specimens' surfaces, 500 N Instron tensile testing machine was used to measure the friction coefficient and is shown in Fig. 1(a). For this purpose, the cubic specimen, to which a pulling cable was connected, was prepared by the load transfer plate placed on the surface. Then, friction coefficient was tested based on ASTM G115-10 [19] specification. Therefore, the friction coefficient was calculated using the formula shown in Fig. 1(b).

It is noteworthy that the conditions on the cubic specimen surface resulting from the load transfer plate are similar to those of the experimental specimen's surface. This also holds true for tensile loading of specimens such that surface conditions of non-sandblasted specimens under class A with unpainted clean mill scale steel surfaces were similar to those of the cubic specimen prepared by the load transfer plate. For specimens with sandblasted surfaces under class B, the cubic specimen was sandblasted as well. It should be noted that the preparation of sandblasted specimen surfaces was continued until changed to uniform silver surfaces. In such preparation quality level, the surface roughness will be higher than other preparation quality levels. With regard to friction coefficient being dependent on the amount of surface roughness, the friction coefficient of all sandblasted specimens exceeded the maximum allowable amount suggested by AISC specification which is equal to 0.5. Table 2 shows the amounts of friction coefficient of specimen surfaces.

2.2. Experiment setup and test arrangement

To apply the axial tensile load on specimens, the test set up shown in Fig. 2(a) was used in which two compressive jacks were applied to create the axial tensile load such that these two jacks were connected to a beam-column with clamp bearing via spacers. The axial tensile load in specimens was made by pushing beam-column with rolling bearing. It is possible to measure momentary load via load cells opposite to the jacks which were connected on a beam-column with rolling bearing. In addition, to control the momentary Stroke lengths of the jacks during loading, the linear variable differential transformer (LVDT's) was mounted beside every jack. Set up members of loading were placed accurately to avoid any eccentricity of tensile load in the specimens. The loading velocity was considered as 1 mm/min for all specimens. LVDT was used to measure the displacement of block shear area as shown in Fig. 2(b) with LVDT-1 and its installation was similar to the method used in the experimental work by Samimi et al. [16]. To install LVDT (Fig. 2(b)), a metal base was used and installed on the specimens by two 4 mm bolts with 48 mm space from the first row of bolts. At the end of the specimen, a displacement bar was installed thus LVDT can be used for measuring. Furthermore, to measure the amount and time of slip of specimens with slip-critical connection, LVDT opposite the specimen was used as shown in Fig. 2(b) by LVDT-2 name. For specimens in which elastic strain gauges were used, the strain gauges were installed between the first row of bolts as this is the most critical area and it fits into the plastic area easier than other parts of the specimen [3,4].

Table 1
Average material properties of test specimens.

material properties of specimens	Thickness	Yield stress	Ultimate stress	$\frac{F_Y}{F_U}$	Young's modulus	Hardening strain	Ultimate strain	Initial area	Final area	Failure load
		F_y	F_u		E	ε_H	ε_u	A_I	A_F	P_F
	(mm)	(MPa)	(MPa)	(%)	(GPa)	(%)	(%)	(mm^2)	(mm^2)	(KN)
A36	7.61	288.4	450.1	64.1	204.4	2.03	16.9	95.73	36.65	29.47
A36	3.99	271.1	389.9	69.5	200.6	2.16	18.6	50.16	17.41	12.94
A572/42	4.05	361.6	456.8	79.2	205.8	1.48	17.3	50.71	18.47	15.15
A572/50	4.01	480.3	536.0	89.6	210.3	1.96	14.2	50.33	21.47	16.55