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Block Shear Experimental and Numerical Studies on Hot Rolled Channel and Gusset Plate with Staggered Bolted Connection

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ABSTRACT

This paper describes the block shear strength of a hot-rolled U-section and gusset plates with a staggered bolted connection based on a series of tensile tests. A formula is presented to calculate the ultimate load of the members in a novel method called "plane decomposition". A comparative study is done between the AISC-2010, Teh and Yazici and plane decomposition methods and the results of the experimental study. This comparison showed that the solutions presented by AISC-2010 and Teh and Yazici are quite conservative, but the plane decomposition method provides acceptable results. Nonlinear 3D finite element (FE) analysis was carried out to determine the stress distribution on the staggered bolted connection. The results show that the staggered planes are simultaneously subjected to shear and tension. The plane decomposition method was validated by the FE results.

1. Introduction

Block shear is a failure mode of members subject to axial tension. In this failure mode, part of the section tears away from the connection in response to a combination of tensile and shear stresses [1]. According to AISC-2010 specifications [2], the block shear capacity depends on the areas of tensile and shear stress. The shear and tensile planes run parallel and perpendicular to the axial load direction, respectively; therefore, accurate prediction of the stress distribution can improve the design criteria.

AISC-2010 specifications present two failure mechanisms for block shear: (i) tension fracture and shear yield; (ii) simultaneous fracture of both shear and tensile planes. The first mechanism has been reported in previous experimental studies [3–6]. Other failure modes have been observed in previous research. In one example, shear fracture (or shear yield) occurs on a shear plane with bending fracture (or bending yield) at the end edge of the member [7,8] and tension yield and shear fracture [9].

In some cases, the bolts are attached to the member in a staggered configuration that can potentially change the failure path through a combination of tensile and shear stresses in each staggered plane. AISC-2010 specifications suggest that the staggered planes of the block shear region are considered to be a tensile plane using rule of $s^2/4g$. This rule was developed by Cochrane [10] for tension capacity, not for block shear capacity. Teh and Yazici [9] improved $s^2/4g$ by applying changes to the formula; however, few studies are available about the block shear capacity of staggered bolted connections.

The current study presents an equation to predict the block shear strength of hot-rolled U-sections and gusset plates with a staggered bolt configuration using experimental and numerical results. The nonlinear finite element (FE) method was used for numerical study. All specimens had symmetrical bolted patterns and the load was applied to the centroid of the connection to avoid load eccentricity. The equation was obtained by resolving the staggered planes into two perpendicular components (i.e. rectangular components of the staggered plane). The results of the proposed equation were compared with those of previous research and experimental and numerical studies.

2. Relevant equations

2.1. AISC-2010 specifications

According to AISC-2010, block shear is a rupture in which it is assumed that the fracture path occurs on the centerline of the bolts and the yielding path occurs in out-of-line of bolts. The net and gross areas are used as fracture and yielding criteria,

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respectively. This specification assumes that the ultimate shear stress is equal to $0.6F_y$. This value has been obtained from the analytical value of ultimate shear stress obtained by the Von Mises criterion, i.e. $\frac{F_y}{\sqrt{3}}$. AISC-2010 presents block shear strength as:

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

where F_y is yield stress, F_u is ultimate stress, A_{nv} is the net area subject to shear, A_{nt} is the net area subject to tension, A_{gv} is the gross area subject to shear and U_{bs} is the reduction factor to approximate the non-uniform stress distribution on the tensile area where the tension stress is uniform at $U_{bs}=1$ and where the tension stress is non-uniform at $U_{bs}=0.5$. When the configuration of the bolted connection is staggered, the net area subject to tension can be calculated as:

$$A_{nt} = \sum\left[g - d_h + \frac{s^2}{4g}\right]t \tag{2}$$

where S is the longitudinal center-to-center spacing (pitch) of any two consecutive holes, g is the transverse center-to-center spacing (gage) between fastener gage lines, d_h is the diameter of the hole and t is the thickness of the member. By substituting Eq. (2) into Eq. (1), the block shear capacity of members with staggered bolt configurations can be calculated as:

$$P_{us} = 0.6F_uA_{nv} + U_{bs}F_ut\left[\sum\left[g - d_h + \frac{s^2}{4g}\right]\right] \le 0.6F_yA_{gv} + U_{bs}F_ut\left[\sum\left[g - d_h + \frac{s^2}{4g}\right]\right] \tag{3}$$

According to Eq. (3), AISC-2010 stipulates that, in a staggered bolted connection, the fracture of the staggered plane and the fracture or yielding of the shear plane occur simultaneously.

2.2. Teh and Yazici solution

Teh and Yazici [9] presented a solution to calculating the block shear strength of cold-reduced steel sheets with staggered bolted connections. Although the cold-reduced steel had lower ductility and F_u/F_y values than the hot-rolled steel, a comparison of Teh and Yazici's equation and other solutions provides food for thought. Teh and Yazici used an active shear plane instead of net and gross planes for which the active shear planes lie between the gross and the net shear planes [11]. They reported two failure modes: (i) fracture of staggered planes and yielding of shear planes and; (ii) fracture of shear planes and yielding of staggered planes. They also ignored the fracture of both shear and staggered planes as presented by AISC-2010. They have suggested a formula for block shear strength based on the tension capacity of the staggered bolted connections [12] as follows:

$$P_{us} = 0.6F_uA_{av} + F_yt\left[\sum\left[g - d_h + \frac{s^2}{4g + 2d_h}\right]\right]\left(0.9 + \frac{0.1d}{g}\right) \le 0.6F_yA_{av} + F_ut\left[\sum\left[g - d_h + \frac{s^2}{4g + 2d_h}\right]\right]\left(0.9 + \frac{0.1d}{g}\right) \tag{4}$$

where d is the bolt diameter, d_h is the bolt hole diameter and A_{av} is the active shear area given as:

$$A_{av} = L_{av}t \tag{5}$$

in which L_{av} is the active shear length and is calculated as:

$$L_{av} = L_{gv} - \left(\frac{n_r - 1}{2} + \frac{1}{4}\right)d_h \tag{6}$$

where L_{gv} is the gross shear length and n_r is the number of bolts in the shear path.

2.3. Proposed equation

This section presents an equation for calculating the block shear strength of staggered bolted connections. It is clear that a staggered plane is simultaneously subjected to shear and tension; therefore, the staggered plane can be resolved into two perpendicular planes as shown in Fig. 1. This method is called "plane decomposition".

Experimental and numerical studies were used to determine the amount of shear and tension in each staggered plane when the plane resolves into two rectangular components: (i) parallel to the load direction (known as shear plane) and, (ii) perpendicular to the load direction (known as tension plane).

The proposed equation for block shear strength of staggered bolted connections is based on AISC-2010. The block shear failure mode of the staggered bolted connections can be considered either as fracture of the staggered planes and yielding of the shear planes or fracture of both the staggered and shear planes. Four areas are introduced as follows:

- The net component of the staggered plane perpendicular to the load direction, A_{nti}, which fails under tensile fracture.
- The net component of the staggered plane parallel to the load direction, A_{nvi}, which fails by shear fracture.
- The net area parallel to the load direction, A_{nv}, which fails by shear fracture.
- The gross area parallel to the load direction, A_{gv}, which fails by shear yielding.

Fig. 1 shows that these areas can be calculated as:

$$A_{nti} = tL_{nti} = tL_{ni}\sin\alpha_i \tag{7}$$

$$A_{nvi} = tL_{nvi} = tL_{ni}\cos\alpha_i \tag{8}$$

By substituting Eqs. (7) and (8) into Eq. (1), the block shear strength of the staggered bolted connections can be calculated as:

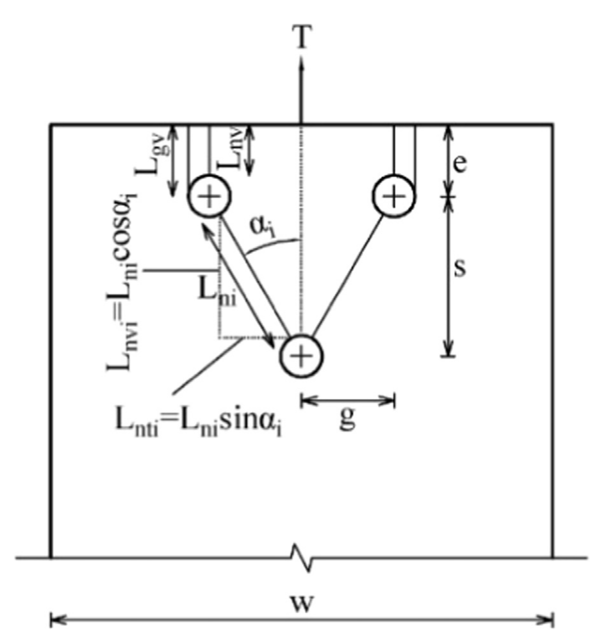

Fig. 1. Rectangular components of staggered planes.