Block shear failure of the gusset plate with a riveted joint

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Abstract

The shear failure of a block is critically limited in axially loaded tension members, typically characterised by rupture of the net tension plane combined with yielding of the gross shear plane, or vice versa. Depending on the length of connections, the governing mechanism may shift to shear rupture with a tension-yielding plane. During service conditions, a structure is frequently subjected to cyclic loading, which results in fatigue failure at a certain stress level below the material's yield strength. In riveted joints, sharp-edged discontinuities around rivet holes induce significant stress concentrations, which in turn promote rapid crack initiation. Primarily, the fatigue failure is governed by crack propagation rather than initiation. This research adopts a fracture mechanics-based approach to study the characteristics of crack growth in a gusset connection. Numerical simulations were performed here to comprehend the behaviour of crack growth due to axially loaded gusset plates with riveted fasteners. Crack initiation is assumed at locations of maximum hot-spot stress, with initial cracks introduced normal to the principal stress direction at rivet holes. Paris' law was employed to evaluate the fatigue crack growth rates while considering residual stress effects, Stress Intensity Factors (SIF), and stress ratios. The Extended Finite Element Method (X-FEM) is employed to simulate crack propagation and estimate fatigue life in terms of the number of cycles required to reach critical crack length. The study provides insight into block shear failure behaviour of tension members with non-staggered holes, highlighting fatigue performance of riveted gusset plates and angles under cyclic loading.

Keywords: Block shear, steel, tension, shear failure, rupture, Fatigue

1 Introduction

Block shear failure occurs from combined tension and shear on perpendicular planes and is recognised as a potential mode in axially loaded tension members [1]. Block shear typically involves rupture of the net tension plane and yielding of the gross shear plane, though in shorter connections, shear rupture with tension yielding may govern. IS 800-2007 [2] defines block shear strength, Tdb, as the lesser of two expressions, but staggered holes are not clearly addressed.

The motivation of this research arose from the catastrophic structural failure documented in the events outlined below

1994 Northridge Earthquake, California: In 1994, the Northridge Earthquake caused brittle failures in steel moment connections and ASTM A325 bolts, as well as bracing frame buckling, tearing, and base plate ruptures, highlighting vulnerabilities in steel structures [3].

Titanic, North Atlantic Ocean: The 1912 Titanic sinking was linked to brittle fracture of slag-rich iron rivets in icy waters, causing hull plate separation and flooding, as confirmed by later metallurgical investigations [4].

This research aims to study the block shear failure behaviour of tension members with non-staggered holes. The purpose of this analysis is to point out the crack initiation pattern of block shear failure of the gusset plate and angle with rivet fasteners under static and cyclic loading. This research aims to study fatigue failure of the gusset plate under cyclic loading and find out the tension members' behaviour. This research aims to conduct a Numerical study on crack growth behaviour and simulate crack propagation in an axially loaded riveted gusseted connection.

2 Methodology

IS 800-2007 [2] considers block shear strength. Tdb of the connection shall be taken as the smaller of the following equations. It is not exactly defined what the stagger holes are

$$T_{db1} = \left(\frac{A_{vg} \times f_y}{\sqrt{3}\gamma_{mo}}\right) + \left(0.9\,\frac{A_{tn} f_u}{\gamma_{m1}}\right) \quad (1)$$

$$T_{db2} = \left(0.9\,\frac{A_{vn} \times f_u}{\sqrt{3}\gamma_{m1}}\right) + \left(\frac{A_{tg} f_y}{\gamma_{m0}}\right) \quad (2)$$

Whereas,
f_y = yield strength of steel (MPa), f_u = ultimate tensile strength of steel (MPa), A_{vg} = net (effective) area in shear (mm²), A_{vn} = net area in shear (mm²), A_{tn} = net area in tension (mm²), A_{tg} = gross area in tension (mm²), γ_{m1} = partial safety factor for ulti-mate stress (usually 1.25), γ_{m0} = partial safety factor for yielding (≈ 1.10).

The expressions mentioned above in Equations 1 & 2 are related to the failure mechanisms and ultimate resistance; they are typically found in IS 800:2007, the Indian Standard Code of Steel Structures, especially in the sections discussing fracture and yielding limit states for bolted connections.

The AISC-ASD [5] and LRFD [6] specifications are used to predict the block shear rupture energy. Inside the AISC-ASD [5] procedure, failure is believed to occur with the aid of simultaneous rupture of the net tension and shear planes. Nominal load capacity without the factor of safety is given below

$$R_n = F_u A_{tn} + 0.6 F_u A_{vn}$$

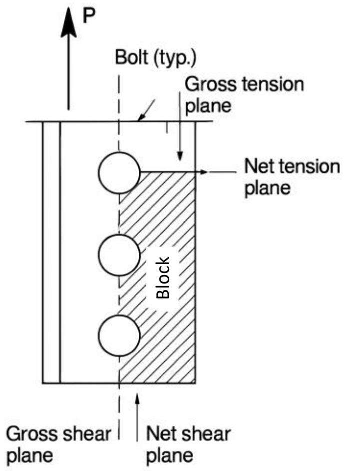


Fig 1. The intersection between A_1 and A_2

Eurocode 3 [7] Specification in Eurocode three pr-EN 1993-1-eight: 20xx, the design for block shear (termed "block tearing" in general) for symmetric bolt agencies, under centric loading is decided from the equation:

$V_{eff}, 1, R_d = \left(\frac{f_u A_{nt}}{\gamma M_2}\right) + \left(\frac{1}{\sqrt{3}}\right) + \left(\frac{f_y A_{ny}}{\gamma M_0}\right)$, $V_{eff}, 1, R_d$= is the effective design shear resistance, γM_2= 1.2 partial safety factor for tension, γM_0 = 1 partial safety factor for shear.

3 Results and discussions

3.1 Determination of Hot-spot stresses

From the stress analysis result, the maximum stress concentration has been determined and shown below. To locate the hot-spot stress, a static analysis has been performed over the gusset-angle jointed connection. A 2D model is considered in Figs. 2, 3, and 4 due to the complexity of the model. In spite of rivets, fasteners are considered for modelling. An edge surface loading is applied at the top edge of the angle.

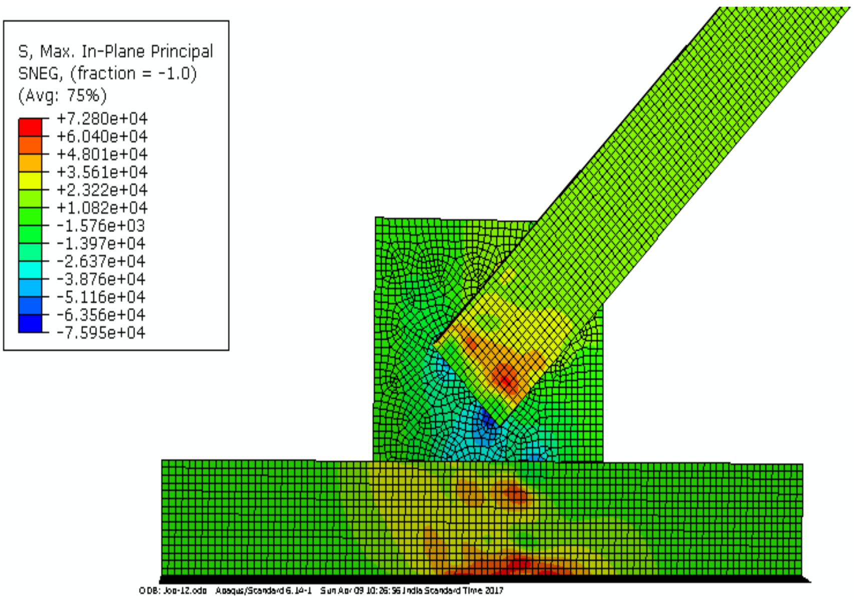
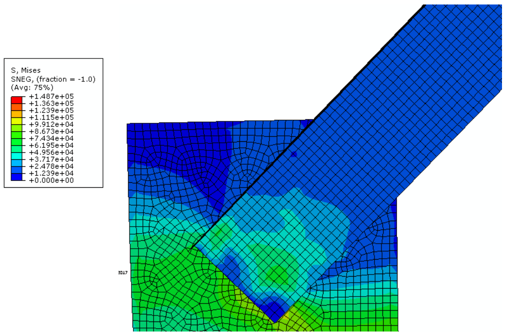
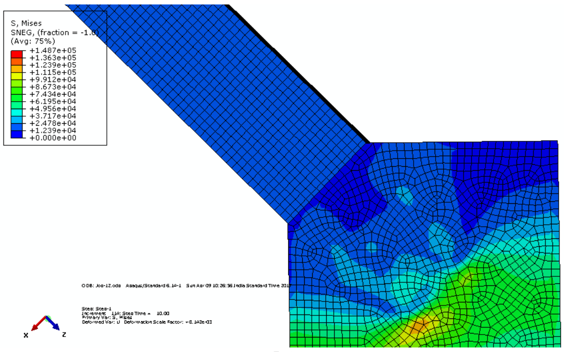


Fig. 2. hot spot stress area and maximum principle stress



(a)

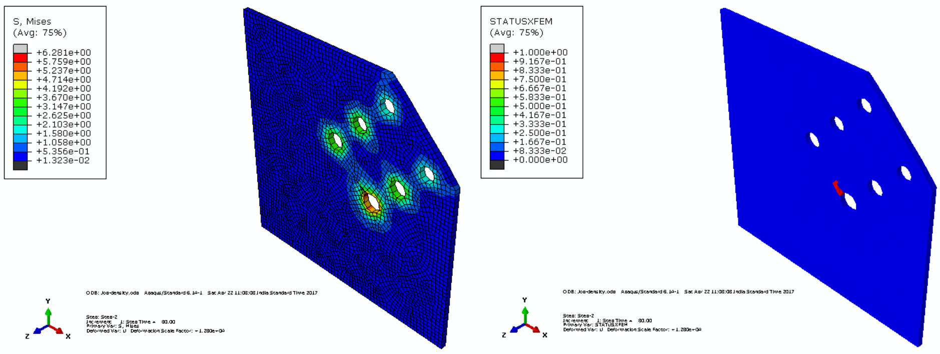


(b)

Fig. 3. (a) Front view showing the overall von Mises stress distribution, and (b) Detailed view highlighting localized stress concentrations on the gusset plate under the applied force.

3.2 Crack growth simulation and fatigue analysis

To simulate crack Growth, XFEM offers new possibilities to the analysis methodology. This methodology has reduced computation time for every increment considered. The requirement of a fine mesh around the crack tip has been met. The refined mesh space is ideally as tiny as possible, however, without an influence on the crack path. A crack part was inserted into the gusset plate at the maximum stress area of the rivet hole, and we have a crack initiation pattern on the gusset plate. A static loading is applied at the gusset plates' rivet hole according to the hot spot stress area. To locate the behaviour of fatigue failure as mentioned in Figs 4&5, periodic form of cyclic loading is computed. In spite of calculating the whole model, we only take the gusset plate.



(a) (b)

Fig. 4. hot spot stress area and maximum principle stress

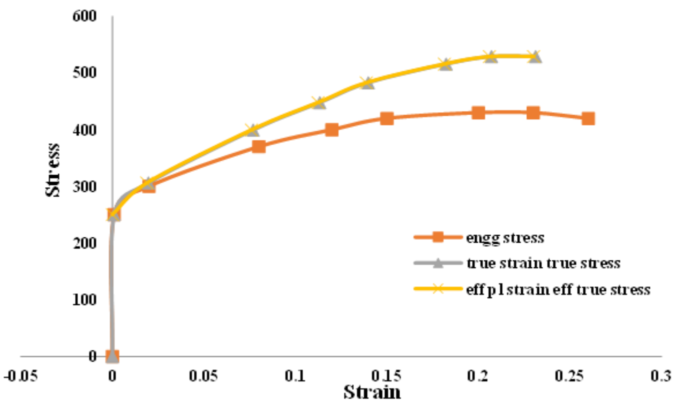


Fig. 5. stress- strain curve

3.3 Fatigue crack growth computation

For fracture criteria and initiation, the maximum principal stress of 78.2MPa was used as a criterion for crack initiation. A simplified 3D model of a gusset plate is considered for fatigue crack growth. The fatigue life, some cycles are equal to the step time, while the critical value is reached. It's mentioned that the X-FEM factors are useful in the location around the initial crack. By the usage of X-FEM, the crack in-crease is completely independent of the mesh. The fatigue crack growth and the Mises stress in the XFEM region are shown in Fig. 6&7. Inside the evaluation, the crack propagates along the route of the best pressure.

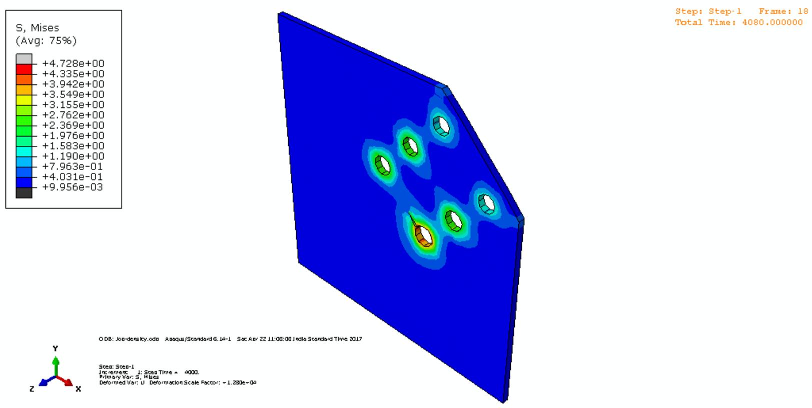


Fig. 6. Mises stress under cyclic loading

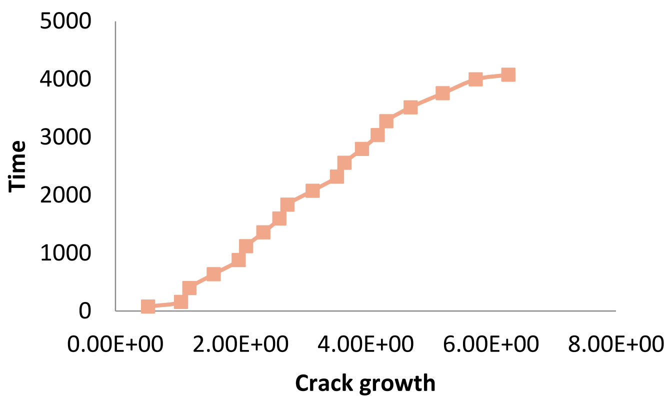


Fig. 7. Mises stress under cyclic loading

3.4 Crack growth computation and loading pattern

Fatigue failure happens beneath a repeated load mentioned in Fig. 8, along with the hysteresis curve in Fig.10, by no means reaching an excessive importance to purpose failure in a single application. The fatigue method embraces two basic domains of cyclic stressing or straining, differing in character and caused by using a specific physical mechanism.

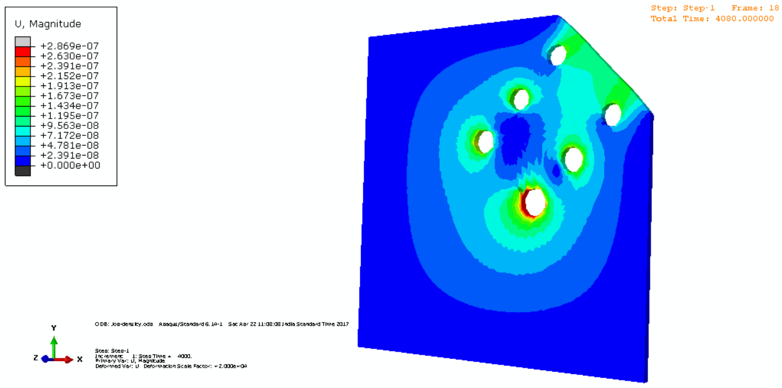


Fig. 8. Displacement

3.5 Fatigue failure due to repeated load

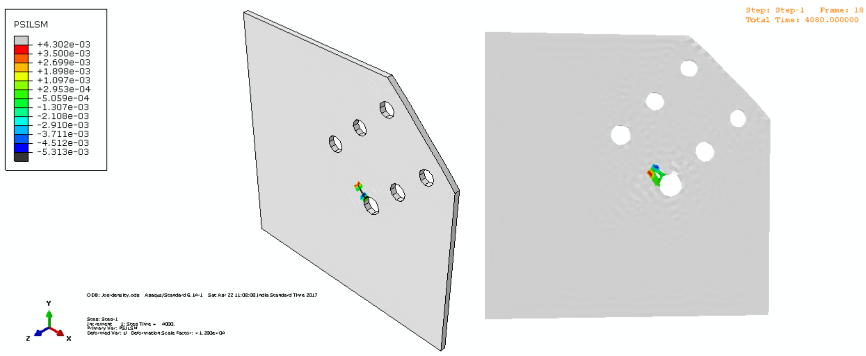


Fig. 9. Crack from a different view

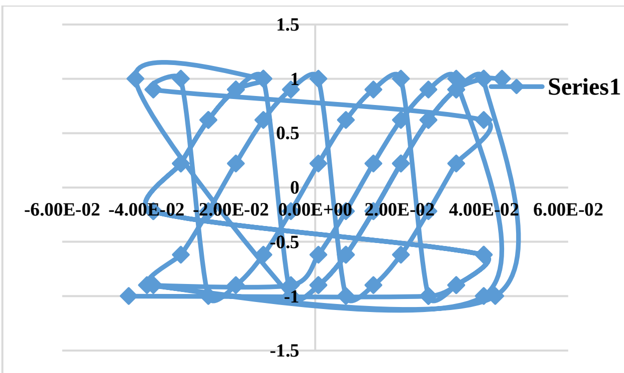


Fig. 10. Cyclic loading

Figs. 9&10 represent Fatigue failure that happens beneath a repeated load, by no means reaching an excessive importance to purpose failure in a single component. The fatigue method embraces two basic domains of cyclic stressing or straining, differing in character and caused by using a specific physical mechanism.

4. Conclusion

An analytical study on block shear failure and fatigue failure of steel tension members was presented in this paper. A finite element analysis methodology was developed to predict the block shear failure load capacities. A gusset plate and angle connection were modelled and analysed with this method. Finite element analysis was found to predict the failure behavior of test specimens. A fatigue failure of a gusset plate with a riveted joint is presented, along with the crack propagation pattern.

This study examined the crack propagation and low-cycle fatigue strength of the angle-to-gusset plate connection in steel bridges.

From this study, the following conclusion can be made.

1. The lower rivet hole at the gusset Plate and angle connection has lower fatigue strength than the upper part of the gusset plate. The principal stress and strain components are maximum at the rivet holes of the lower end of the gusset plate

2. The fatigue crack starts from the rivet hole in the bottom end of the gusset plate, and then it propagates to the upper hole of the plate and connection.

3. From this study, it is shown that the block shear failure behaviour is initiated from the base part of the rivet hole of the gusset plate with axially loaded angle.

4. Block shear load capacity is influenced by the ultimate yield ratio, boundary conditions, and length of the connection. Please try to avoid rasterised images for line-art diagrams and schemas. Whenever possible, use vector graphics instead (see Fig. 1)

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