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The use of punched holes in bridge structures

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The use of punched holes in bridge structures in load-carrying members is not allowed unless the holes are sub-punched to a smaller diameter and then reamed to full size. Some owners allowed full size punched holes in cross frames and lateral bracing systems since these members were not designed to carry a calculated load. Three-dimensional analyses of bridges resulted in calculated forces in these members and the recognition that cross frames carry substantial forces, particularly in curved or skewed girder bridges. Consequently, punching of holes in these members was no longer allowed since they carried calculated design forces. A large experimental study was undertaken to evaluate the impact of punched holes upon the tensile capacity, bearing strength, block shear strength, and fatigue strength of members with punched holes. The study included the effect of plate thickness, hole size, punch clearance, and yield strength upon the strength and ductility of the plates. Recommended design values were developed that account for the lower strength exhibited by members with punched holes. In addition, due to the lower ductility of members with punched holes, they are not recommended for use in main load-carrying members.

Keywords: punched holes; tensile strength; bearing; fatigue; bridges

1. Introduction

Punching of holes in a structural member is a fast and economical method of forming holes for connections. Many fabricators have automated punching and shearing equipment for the angle members typically used for cross frames and other bracing members such as the top lateral system used in composite box girders. The AASHTO specifications (AASHTO 2004a) require holes in load-carrying members to be either drilled full size or sub-punched and then reamed to full size. Secondary members where the forces were not calculated were allowed by some owners to have the holes punched full size. The advent of three-dimensional analyses of bridges has lead to the recognition that these secondary members carry significant loads. They play a major role in the strength and stability of curved and skewed bridges during construction and to a lesser degree in the completed bridge. These secondary members now come under the heading of load-carrying members and cannot have holes drilled full size.

The purpose of the study presented in the paper was to develop rules for the design of members with holes punched full size. The study evaluated the performance of specimens under static and fatigue loading. The study investigated the influence of hole size relative to plate thickness, strength of plate material, punch clearance, test temperature, and fabricator versus laboratory punched holes. The details of the study are contained in Lubitz (2005), Brown (2006) and Cekov (2006). This paper summarises the results and presents new design recommendations.

2. Hole making

The punching process and the associated damage to the base metal have been analysed in past research. For example, a detailed investigation into the effect of the punching process on the tool life of the punch itself was performed by Luo (1999). The steps used to describe the punching process are displayed in Figures 1–3. Luo categorised the behaviour of the base material as it is being punched into three major phases of damage. The first phase involves elastic then plastic deformation of the base metal as it first comes in contact with the punch. During this phase, the bottom of the base metal starts to bend outward from the force of the punch. The second phase is the punch penetrating into the base metal and material starts to

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be sheared outward. An initial small amount of the base metal is sheared, and then a crack begins to propagate as the metal is continually forced downward into the die. A shear band is formed at the top of the base metal from the contact with the punch. This is shown in Figure 1 as Steps A and B. At some point during the punch penetration, a secondary shear zone develops, as shown in Figure 2 as Step C. The metal being forced into the die is sheared by the cutting surface of the die. The location of this secondary zone is dependent on the clearance between the punch and the die and to a small extent on the strength of the base metal. The final phase is the fracture of the slug out of the punched hole. A crack is formed at the top of the base metal due to the shear force caused by the punch, which combines with the fracture crack from the cutting surface of the die. This is shown in Figure 2 as Step C and D. The final step shown in Figure 3, Step E, where the final hole, and associated slug, is formed (Luo 1999).

The appearance of a punched hole is largely dependent on the clearance between the punch and the die. Recommended die clearance increase with plate thickness with 1/32 in. clearance recommended for up to 1/2 in. material and 1/8 in. clearance for 1 in. plate. The work required to punch a hole with insufficient clearance is much larger than with a properly sized die. An excessive die clearance amount results in a larger fracture surface and a large shock when the punch breaks through the material. The shock that results can decrease equipment life and increase maintenance costs. In addition, excessive clearance causes the cutting surface of the punch to break down prematurely.

Examples of the work required to punch multiple hole sizes with various die clearances through multiple thickness and grades of steel were investigated and are presented in Brown (2006). The punch force versus punch displacement values were recorded during the punching process for this project. These figures illustrate that the work required to punch a hole is partially dependent on die clearance. One example is shown in Figure 4. The figure shows punch force and displacement for a 1/2 in. A36 steel plate with a 15/16 in. diameter hole, punched with various die sizes. The recommended die clearance for 1/2 in. thick steel of 1/32 in. (31/32 in. die) required a slightly higher punch force and greater work, as indicated by the area under the load versus displacement curve, than the other recommended die clearance value of 1/16 in. (32/32 in. die). The predicted force, using the empirical method was 82.3 kips, using 0.8 times the tensile strength of the material, 69.9 ksi, times the hole circumference times

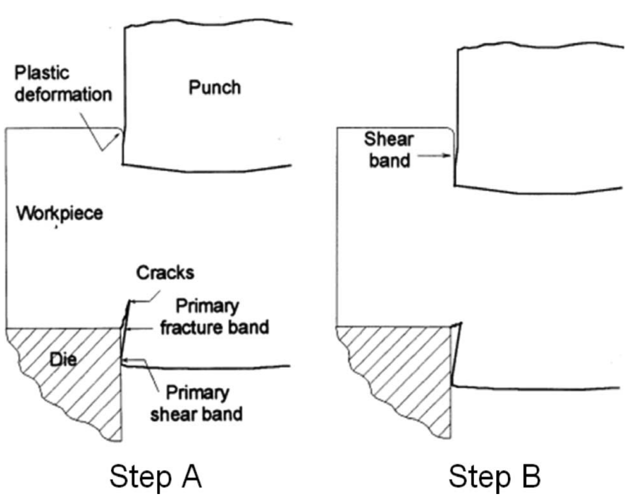


Figure 1. Hole punching: Step A and Step B (Luo 1999).

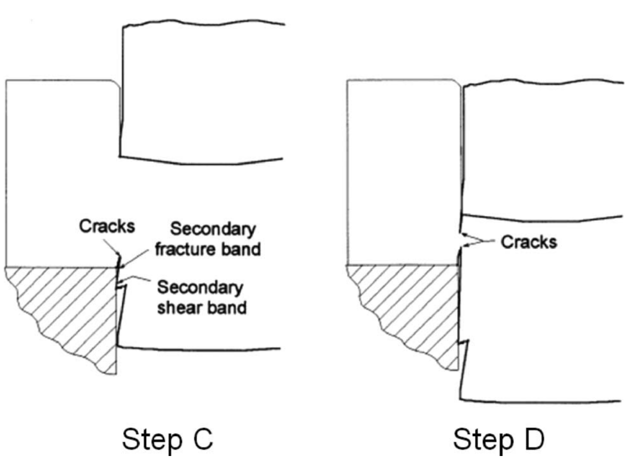


Figure 2. Hole punching: Step C and Step D (Luo 1999).

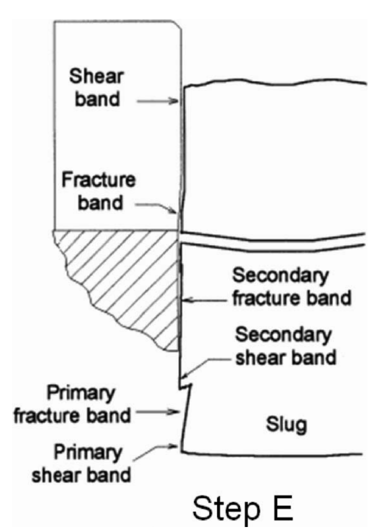


Figure 3. Hole punching: Step E (Luo 1999).

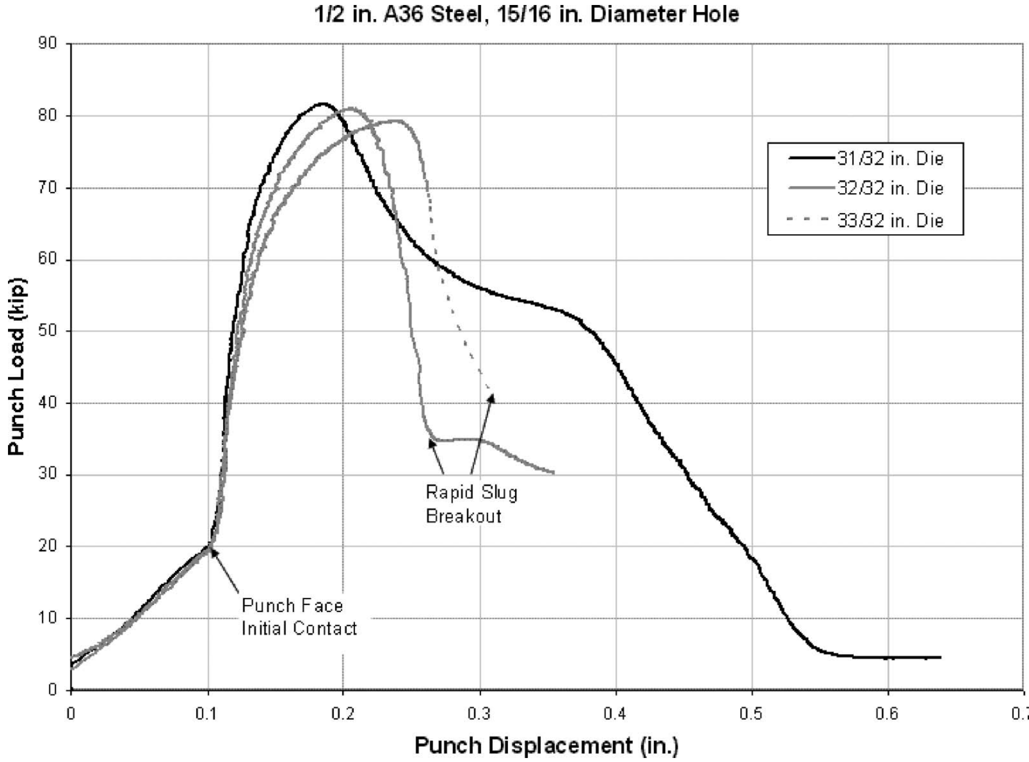


Figure 4. Punch force versus displacement – 1/2 in. A36 steel.

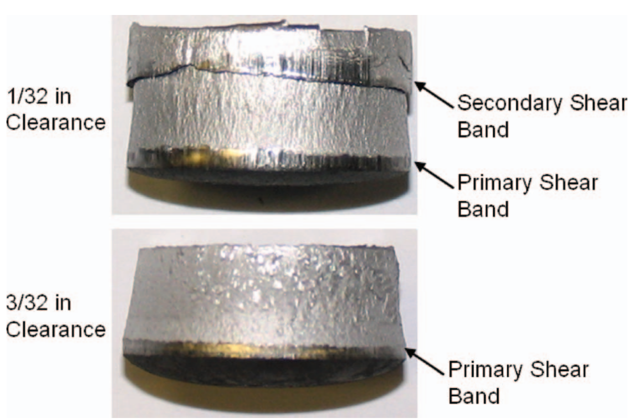


Figure 5. Typical punched hole slugs.

plate thickness. The actual maximum punch force was 79.2–81.6 kips for the three die sizes shown.

The effect of hole clearance is shown in the two slugs shown in Figure 5. Both slugs are from a 1/2 in. thick A572 Grade 50 plate. The top slug was made with a 15/16 in. diameter punch with a 31/32 in. die (clearance 1/32 in.), while the bottom slug was made with a 15/16 in. diameter punch with a 33/32 in. die (clearance 3/32 in.). The top slug with the secondary shear band is from a hole punched with a proper sized die, while the bottom slug with just a primary shear band corresponded to a die size that provides an excessive clearance amount, 3/32 in. instead of 1/32 in. or 1/16 in. The associated morphology of the hole is shown in Figure 6. The fracture band on the cross-section of the hole was much larger when the die clearance is greater than ideal. The shear band in the cross-section was related to the amount of penetration from the punch. For the cross-section with a small shear band at the top, the punched hole slug was suddenly fractured out of the base material once the fracture crack initiated. Another important fact, shown in Figure 6, was the larger hole diameter at the bottom of the hole compared to the top, which resulted from the fractured surface propagating at an outward inclined angle, thus increasing the effective diameter of the punched hole. This amount varies with steel grade, material thickness, and die clearance. These figures represent typical punched holes formed during this research project. Die clearance was used as a variable in this research project since the AASHTO specification limits the clearance to 1/16 in.

Figure 7 compares the finish of holes made by drilling and reaming a punched hole. The finish of a drilled hole was found to be dependent upon the wear of the drill bit. The holes in this research project were made using a 'slugger' type hollow shell mill bit. The reamed holes made by first punching the holes and the reaming to full size using a tapered bridge reamer. A study of the amount of reaming necessary to remove the effect of punching was negligible and only 1/16 in. was required. The current specification value is 3/16 in., which was found to be adequate.

3. Tensile strength tests

The effect of hole making upon the tensile strength was done using plate test specimen with two holes at the net section. The specimen was designed to fail by fracture through the net section. The effect of plate thickness, edge distance of the holes, temperature, and plate strength as well as hole size were examined. The influence of die clearance, reaming, fabricator versus laboratory punched specimens, and drill wear were also evaluated. The effect of punched holes upon the performance of the specimens was done by testing replicate specimens with drilled holes.

Typical failed specimens are shown in Figure 8. The specimen on the left had punched holes and the one on the right had drilled holes. These are otherwise identical specimens. The specimen with drilled holes failed in a more ductile manner than the specimen with punched holes as evidenced by the necking of the specimen. This ductility is also evident on the fracture surfaces shown in Figure 9. The thickness contraction at the fracture is almost nil in the punched hole specimen.

The strength of the plates with punched holes was found to be consistently less then replicate specimens with drilled holes. A typical load versus testing machine cross-head displacement is shown in Figure 10. The lower load of the specimen with punched holes is evident as well as the lower deformation capacity. This difference in behaviour between the two types of holes was typical of all the replicate tests. Typically the strength of the lower strength A36

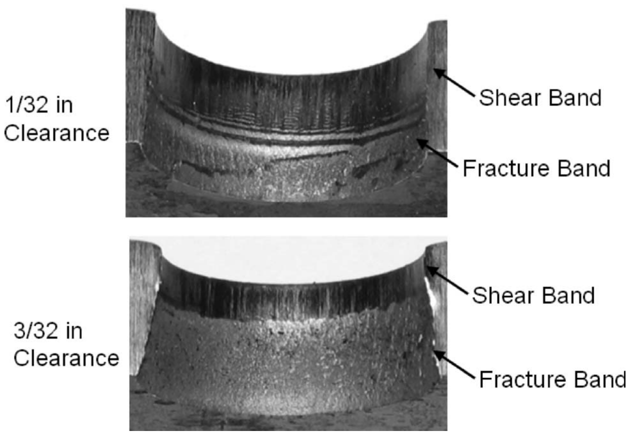


Figure 6. Typical punched hole cross-sections.

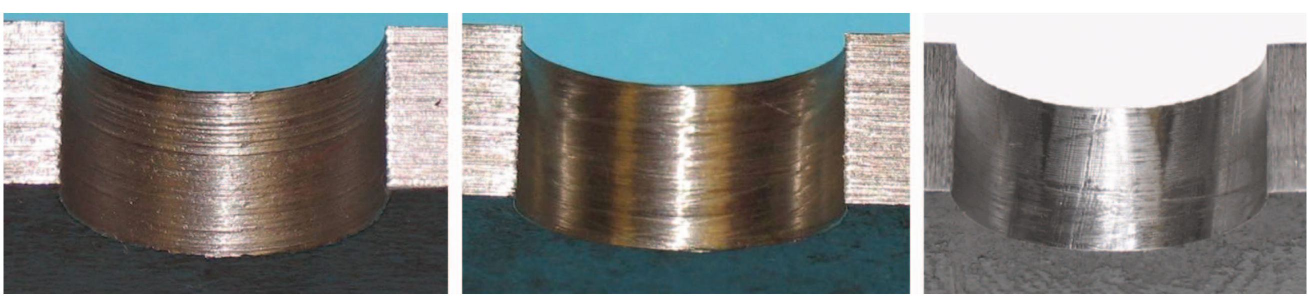


Figure 7. Hole finish. Left to right: worn drill; new drill; and punched and reamed.

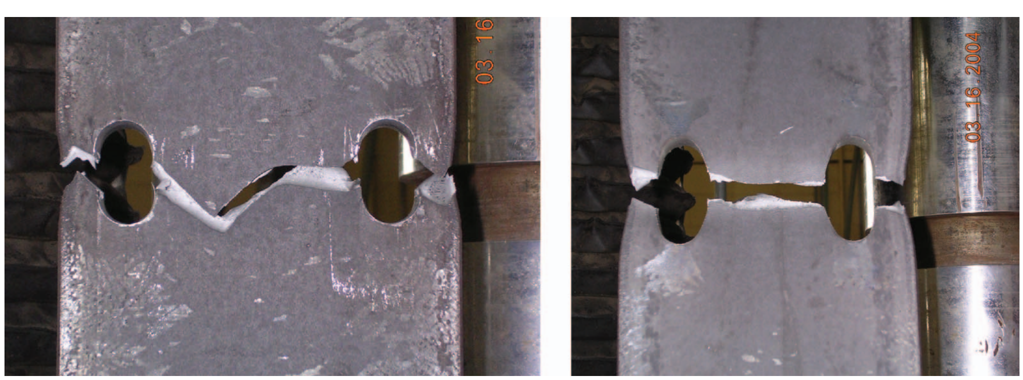


Figure 8. Punched and drilled hole fractured specimens.

plates with punched holes fell below the specification strength calculated as the tensile strength times the net area at the holes. The grade 50 specimens had higher strength relative to design strength. The grade 50 material with drilled holes typically failed at net section stress above the tensile strength of the material. Specimens with punched holes failed at a lower strength near the design strength. A comparison of the test results with the specification limit of fracture of the net section is shown in Figure 11. The top part of Figure 11 show the results for A36 steel and the lower part show the results for grade 50 steel. The only data below the design values for all the steels were plates with punched holes. The effect of increasing the hole diameter by 1/16 in. as required in the specification did not change the correlation with predicted values. Increasing the hole size had a negligible influence upon correlation even when it was increased by 10%. A 10% reduction in strength was found to be the best estimate of the effect of hole punching upon the predicted strength. It is recommended that the practice of increasing the hole size by 1/16 in. be eliminated in net section calculation and the tensile strength of members with punched holes be taken as 90% of their present design values.

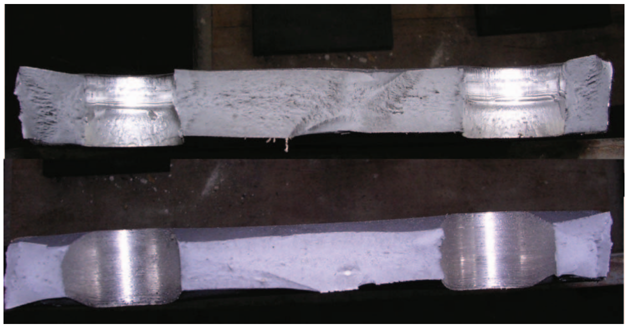


Figure 9. Fracture surface of punched and drilled specimens.

The reduction in ductility exhibited by the plates with punched holes relative to ones with drilled holes was large. A histogram of the ratio of the deformation at maximum load between the punched and drilled specimens is shown in Figure 12. The ratio showed a large variance with the mean values 37% and 63% for the two steels.

4. Connection tests

Connection tests were undertaken to examine the influence of hole making upon the bearing and block shear capacity of the connection. The tests revealed that the bearing capacity and ductility was of the connection with punched holes was less than drilled holes. Figure 13 show a histogram of the bearing

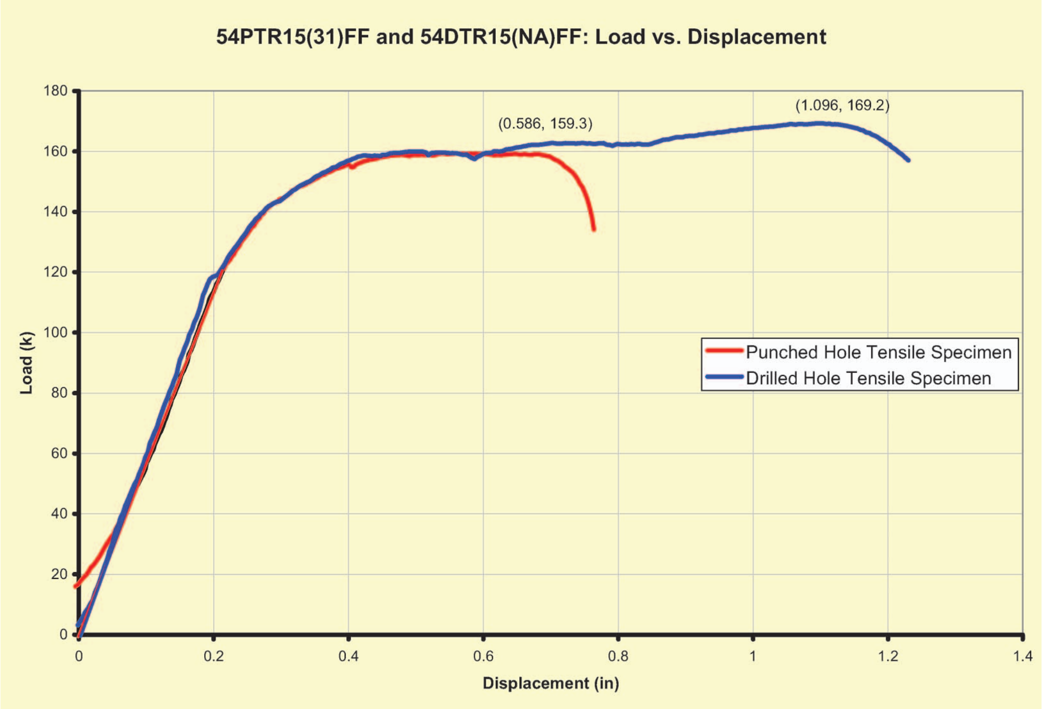
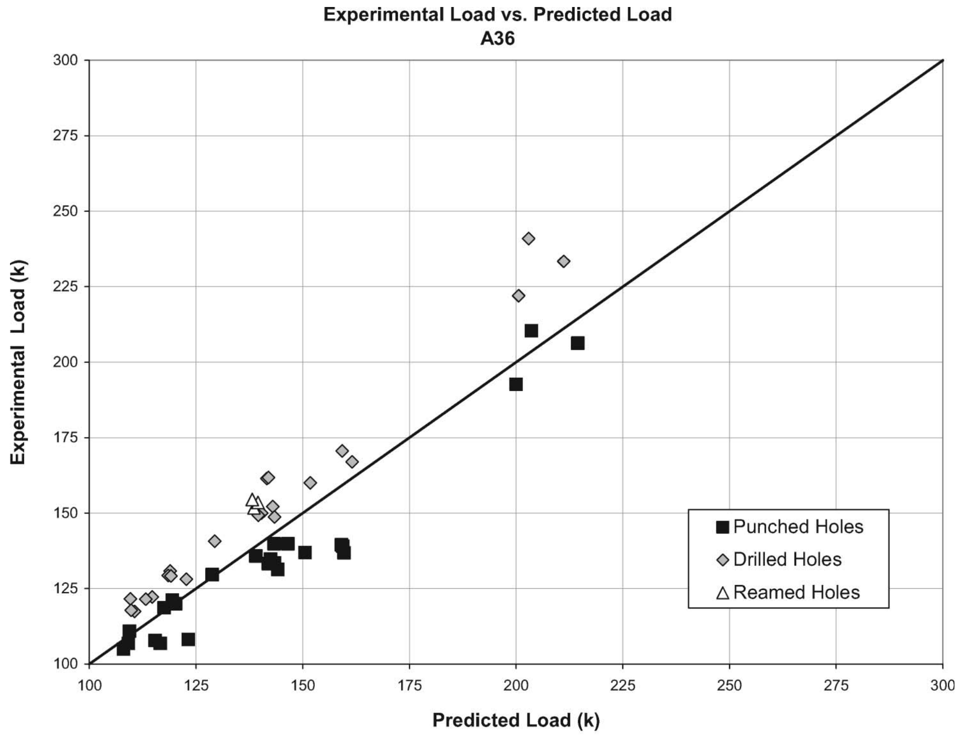


Figure 10. Typical load deformation behaviour of tensile specimens.



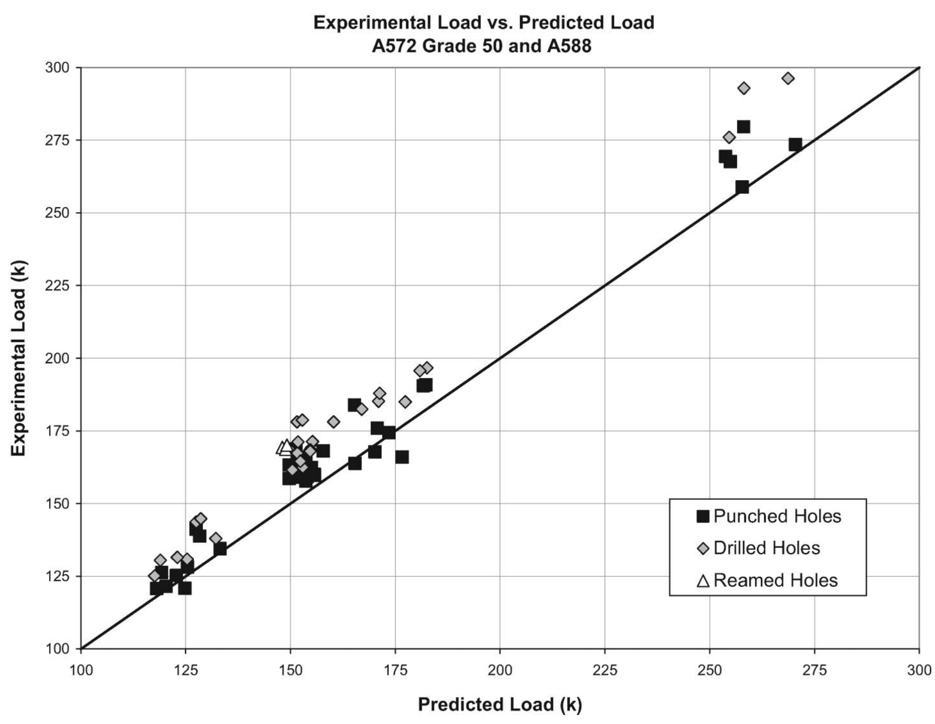


Figure 11. Comparison of tensile strength with predicted specification strength for (top) A36 steel and (bottom) for grade 50 steel.

connection result plotted as the test load divided L_c (the clear distance from the hole to end of the plate) $\times$ t (the thickness of the plate) $\times$ F_u (the tensile strength of the plate). The AISC specification (AISC 2005) gives two values for calculating the bearing capacity. If deformation of the connection is a concern the bearing capacity is given as $1.2 \times L_c t F_u$, which is also the limit in the AASHTO specification

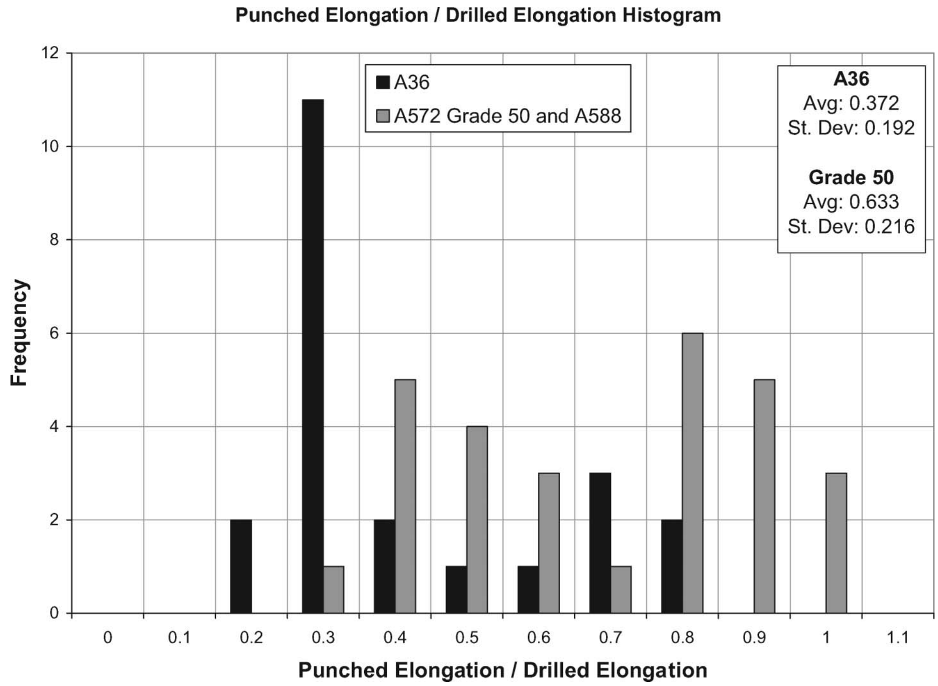


Figure 12. Elongation of tensile specimens.

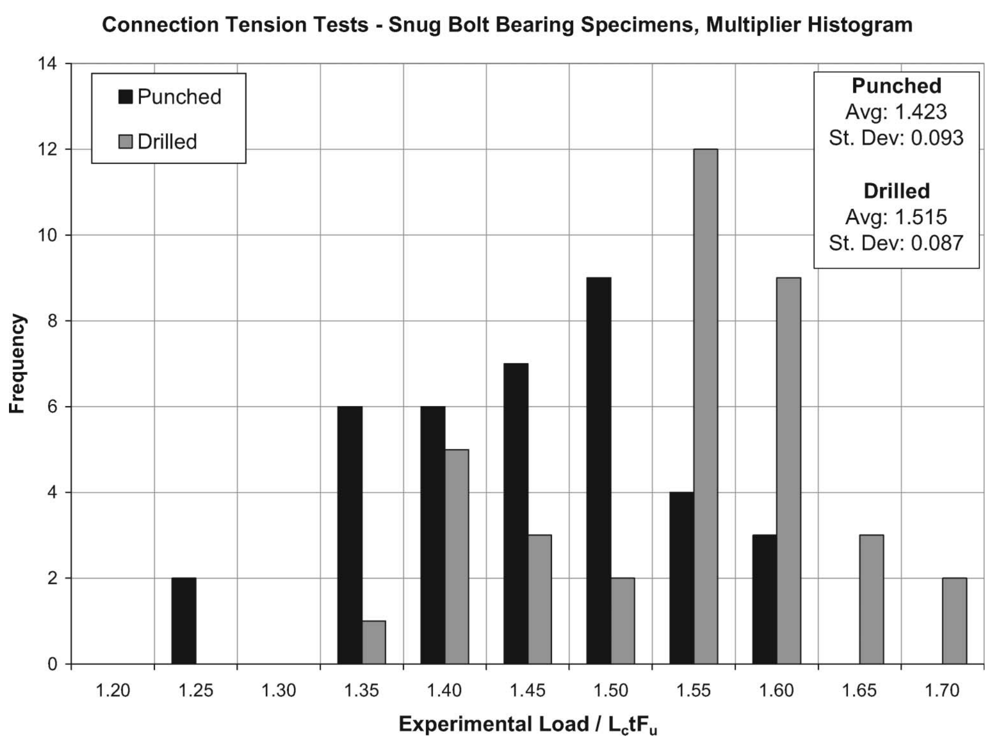


Figure 13. Bearing strength.

(AASHTO 2004b). If deformation is not a design consideration, AISC increases the multiplier to 1.5. Many of the punched specimens and some of the drilled specimens had capacities below the value of 1.5. It is recommended that the present AASHTO specification limit of 1.2 be retained for all connections. The bearing

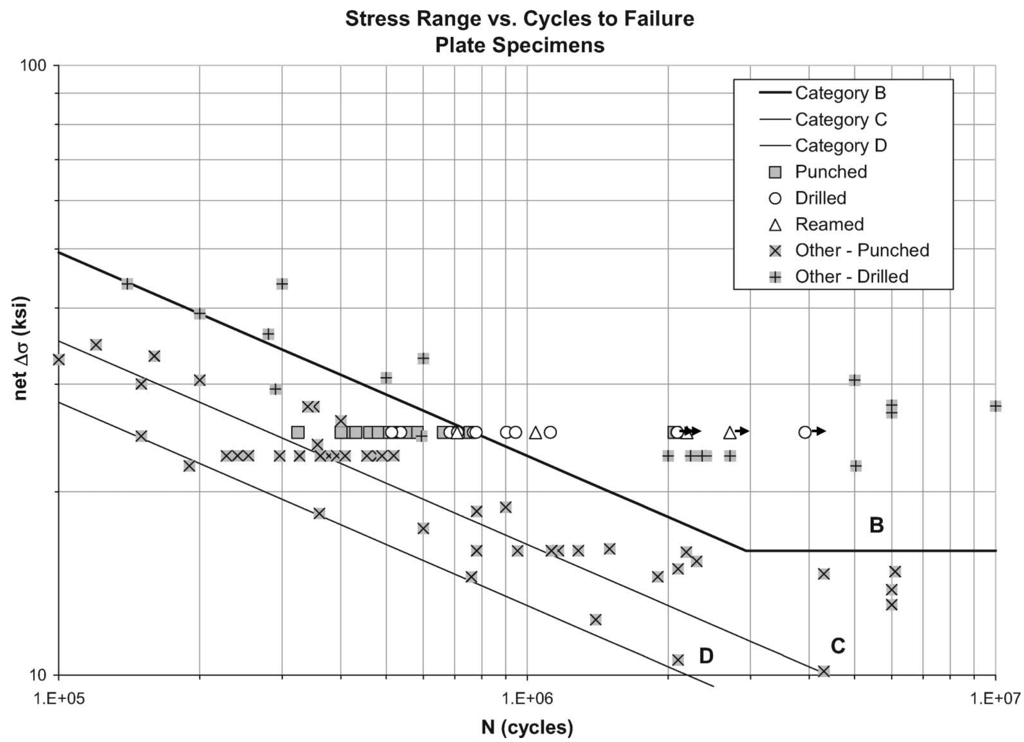


Figure 14. Plate fatigue results.

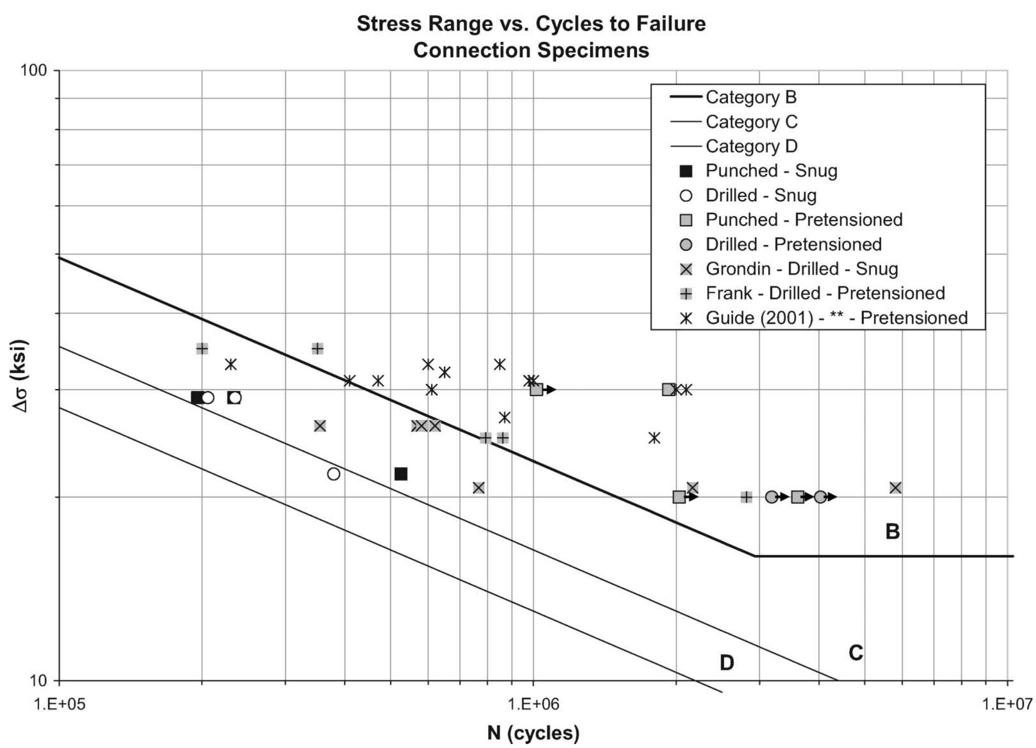


Figure 15. Connection fatigue results.

deformation at maximum load was also less with punched holes, similar to the tension specimen behaviour.

The block shear specimens with punched holes had a slightly lower strength then the replicate specimens with drilled holes. In addition, the block shear provisions of 2005 AISC provided the best estimate of the connection strength. The new provision does not include a limit of yielding on the tensile section and is shown below:

$$R_n = 0.6F_u A_{nv} + U_{bs} F_u A_{nt} \leq 0.6F_y A_{gv} + U_{bs} F_u A_{nt} \quad \text{(J4 - 5)}$$

5. Fatigue results

The fatigue tests revealed that the fatigue strength of plates with holes in them was less than the strength of the same plates used in a connection pretensioned bolts. The fatigue strength of the plate specimens with punched holes had a large scatter. The fatigue strength was influenced by the finish of the hole. Plates with drilled holes using a worn bit gave fatigue lives comparable or worse than the same plate material with punched holes. The fatigue strength connections with snug tighten bolts was less than fatigue category B while connections with pretension bolts had strength exceeding category B. The fatigue test results of this study as well as others (Alegre *et al.* 2004; Huhn and Valtinat 2004; Grondin *et al.* 2004; Gutierrez-Solana *et al.* 2004) are plotted in Figures 14 and 15. Based upon these test results, the fatigue classification of connections with snug or low strength bolts or members with open holes should be category D. Slip-critical connections with pretensioned bolts have a fatigue strength equal to category B. The influence of hole making upon fatigue strength is not apparent in the connections with pretensioned bolts. However, it is recommended that all connections with punched holes be classified as category D.

6. Conclusion and design recommendations

The test results for this study as well as others indicates that the strength and ductility of connections and plates with punched holes is less than the same plates and connections with drilled holes. It is recommended that due to the reduction in ductility that full size punched holes should not be used in members that rely upon connection ductility for performance. There it is recommended that punched holes only be used for secondary bracing members such as cross frames, diaphragms, lateral systems, and other non-primary load members. The tensile strength and block shear of these members should be taken as 0.90 times the specification value.

The fatigue strength of open holes, connections with snug or lower strength bolts, or connections with punched holes should be classified as fatigue category D.

The addition of 1/16 in. to the diameter of the hole when calculating the net section should be eliminated. This small adjustment does not account for the reduction in strength from punching a hole. The net section should be calculated using the nominal hole diameter.

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