Effect of Hole-Making on the Strength of Double Lap Joints

NESTOR IWANKIW AND THOMAS SCHLAFLY

BACKGROUND

Engineers familiar with structural steel and the available fabricating operations have expressed concern over the effect various hole-forming methods have on the ultimate strength of bolted connections, in particular, the use of flame-cutting. In response to these concerns, AISC had conducted tests comparing the performance of connections with holes made by six commonly used methods. The intent of the comparison is to determine whether a need exists to restrict the use of specific hole-making methods and whether connections using holes made with particular methods have any structural advantages.

This portion of the study addresses only standard holes subjected to gradually applied loads and compares the following hole-forming methods:

1. *Punching.* The punch offers the fastest and lowest cost hole the fabricator can make, but is limited to thinner members and is usually restricted to shop use because of the size and lack of portability of the equipment. Current fabricating standards restrict the diameter to the thickness ratio of punched holes, and some qualify the type of member punched, or allow punching only in statically loaded structures. Shearing action of the punch distorts the material in the vicinity of the hole and may leave a cold worked condition with reduced ductility and toughness. Recent research published in Great Britain (Ref. 1) indicates that no decrease occurred in the ultimate strength of connections with punched holes for static loads.

2. *Punching with the burrs removed.* Normally burrs left by any operation would be ground off as a matter of workmanship and to avoid conditions hazardous to other workers. Some questions have been raised whether or not the presence of burrs affects the performance and strength of joints. It has been speculated that burrs could conceivably support the head of the bolt and the washer, reducing the friction in the connection plate material and thereby failing to distribute the connection load evenly around the hole.

3. *Sub-punching and reaming.* When a large connection requiring a close tolerance is encountered, the fabricator may choose to punch holes in the normal fashion, but $1/8$-in to $1/4$-in. under the final diameter, and then ream the hole to its required size. Various specifications may also require that punched holes be reamed to remove material affected by punching.

4. *Drilling.* Drilling is another one of the usual methods of forming holes. The drilling operation has very little effect on the surrounding material. While the drilling of an individual hole is time-consuming, the process is used: (a) when the material is too thick for punching; (b) when items can be stacked, clamped and drilled with a single setup, thus reducing handling while increasing uniformity of pieces; (c) or when a small number of holes is required, making it easier to move a portable drill to the piece rather than move the piece to the equipment.

5. *Flame-cutting.* Since most workers dealing with structural steel keep cutting torches readily available, the flame cutting of standard bolt holes is frequently an attractive option for expedient hole additions or corrections. Slots in heavy material may be formed by drilling one or both ends of the slot and removing the material between the drilled holes by flame cutting. Concerns relative to burned holes center around the workmanship and the effect of heat on the surrounding material. Burned holes are not as smooth in finish appearance as drilled or punched holes. The resultant notches are suspected to act as stress risers that may have a detrimental effect on the strength of the connection. Another question is whether a heat-affected zone with a modified brittle microstructure in the vicinity of the hole remains after flame-cutting.

Nestor Iwankiw is Assistant Director of Engineering, American Institute of Steel Construction, Inc., Chicago, Illinois.

Thomas Schlafly is Assistant Chief Engineer, Flint Steel Corporation, Tulsa, Oklahoma.

6. *Flame-cutting and reaming.* Burned holes can be reamed to remove the notches and the heat-effected material left by the cutting operation. Holes are originally flame-cut to a diameter $^1/_8$-in. to $^1/_4$-in. less than required and reamed to full size similar to the sub-punch and reaming operation.

In the design of standard bolted connections, the AISC *Specification* calls for a check of the following modes of failure: bolt shear, bearing, end and edge distances, block shear and net section tension. All but one of the failure modes depend on the properties of the material surrounding the hole. The remaining mode, bolt shear, depends strictly on the fastener characteristics and is not affected by the condition of the connected material. Bearing criteria do not govern design loads in typical connection details as frequently as the other items checked. Lower ductility expected in the area worked by the punch should have a negligible effect on performance of bolts in bearing on connected material, because compressive strength is not affected by brittleness. The waviness of burned holes should not change bearing strength in a significant way, because the harder bolt material merely presses into the softer connected material, forcing the material to conform to the bolt shank, regardless of original surface condition or hole making process.

End and edge distances are formulated by AISC in recognition of the results of tests which showed that bearing strength is also correlated to these factors. Since these distances are detailing variables not dependent on the hole formation method, they were not considered to be parameters of this study.

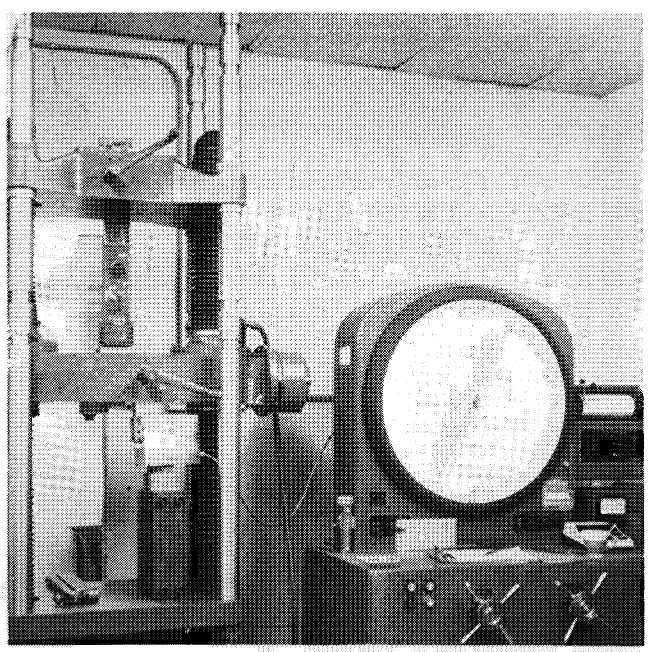

Fig. 1. Illustration of test apparatus used to test 18 specimens. Specimen (upper left) is bolted to fixture

The mode of failure expected to reveal the most dramatic variation in connection performance due to different hole types was tension on net section. At a cross section containing a hole, the stress due to tension is not uniform. Instead peak stresses occur adjacent to the hole. Any reduction in ductility could possibly initiate cracking. Thus, for the purposes of these comparative tests, samples were designed to fail in tension on the net section.

A double lap joint was selected as the bolted connection to be tested in order for the symmetry to minimize any possible load eccentricity effects.

TEST ASSEMBLY

The objective of the experiments (Ref. 2) was to test three samples of each of the following six standard hole-making methods to determine their effects on the static strength of double-lap joints:

	Specimen numbers
1. Punched full size with burrs	P1, P2, P3
2. Punched full size with burrs ground off	P4, P5, P6
3. Subpunched and reamed	P7, P8, P9
4. Drilled	P10, P11, P12
5. Flame-cut and reamed	P13, P14, P15
6. Flame-cut full size	P16, P17, P18

An illustration of the test apparatus is shown in Fig. 1. The 18 specimens were all $^1/_2$-in. thick, 3 x 12-in. A36 material. Two holding units consisting of two $^3/_8$-in. thick, 3 x 12-in. Grade 50 plates fillet-welded to a single $^9/_{16}$-in., 4 x 6-in. plate were reused for nine tests each. The size of the standard holes made by each of the aforementioned procedures was $^{15}/_{16}$-in. diameter. The different hole-making operations at the Inryco Structural Fabricating Shop in Melrose Park, Ill. were witnessed by the responsible staff engineer from the independent testing laboratory, Taussig Associates.

For specimen groups 3 and 5, the holes were sub-punched and sub-burned to $^{13}/_{16}$-in. dia. and then reamed to full size. Representative photographs for each of the hole types prior to testing are shown in Figs. 2–7. The holes were centered in the plates within an edge and end distance of $1^1/_2$ and 3 in., respectively. The hole fabrication for a given group of specimens was performed in a reasonably identical manner. While the burrs were not measured, they appeared to be less than $^1/_{16}$-in. high.

The double-lap joints were fabricated by bolting the holding unit to the middle plate test specimen with $^7/_8$-in. ASTM A325 high-strength bolts with threads excluded from the shear plane. A load indicator washer installed adjacent to the bolt head was used to measure the applied bolt pretension. A hardened flat washer was installed next to the turned element, the nut. Prior to installation and testing, the load indicator washer was calibrated with the

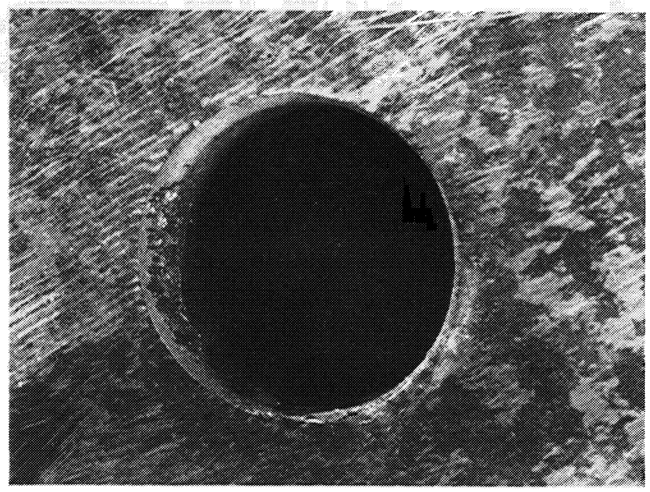

Fig. 2. Hole in Sample P3 made by punching

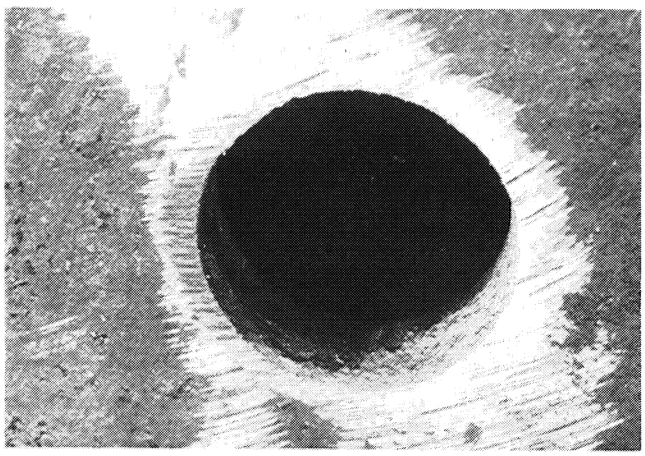

Fig. 3. Hole in Sample P5 made by punching and grinding off burrs

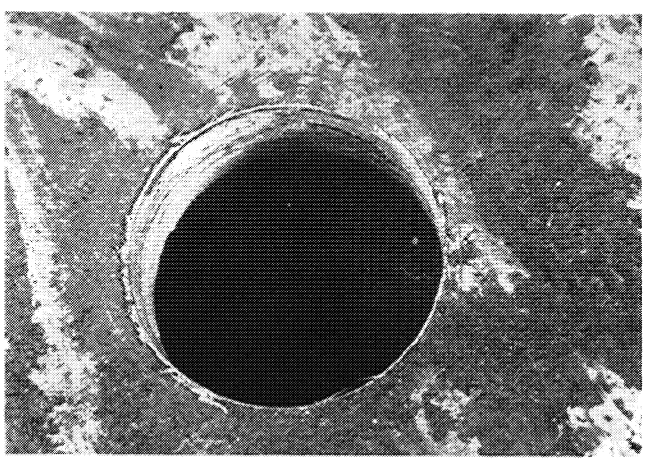

Fig. 4. Hole in Sample P7 made by sub-punching and reaming to size

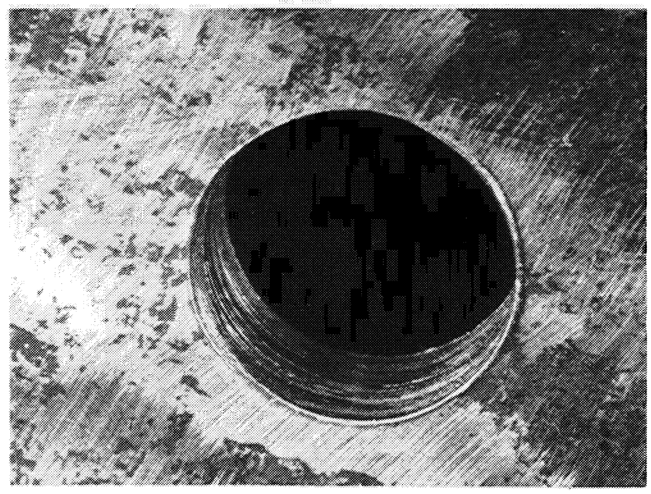

Fig. 5. Hole in Sample P10 made by drilling

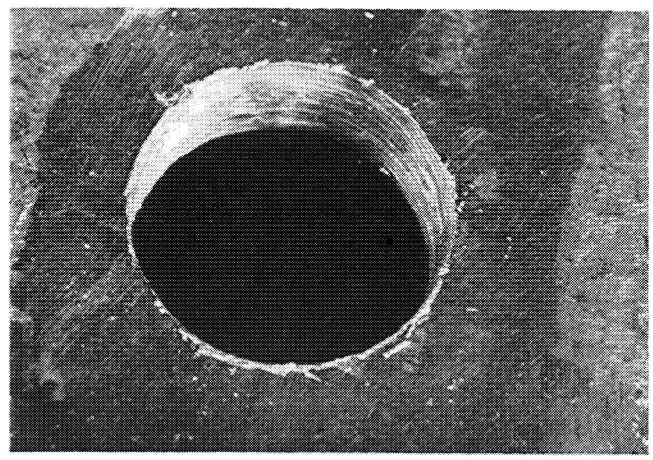

Fig. 6. Hole in Sample P15 made by flame-cutting and reaming to size

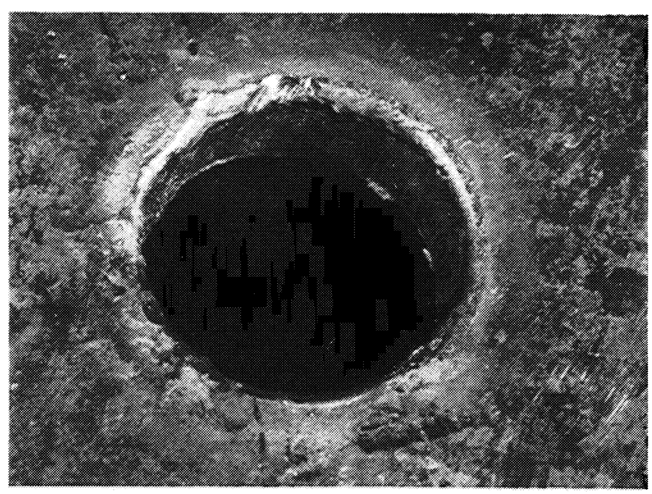

Fig. 7. Hole in Sample P18 made by flame-cutting

use of the testing machine. It was determined that a gap of 0.018 in. corresponds to a load of 39,000 lbs. In accordance with the *Specification for Structural Joints Using ASTM A325 or A490 Bolts*, the ⅞-in. A325 bolts were pretensioned in the joints to the 39,000 lbs. minimum required. A new bolt, load indicator washer, and nut were used with each test specimen. The holding fixtures and hardened washers were reused.

As previously discussed, the test connection was designed in compliance with the 1978 AISC *Specification* for a middle plate net section tensile failure. A sketch of the double lap joint is shown in Fig. 8.

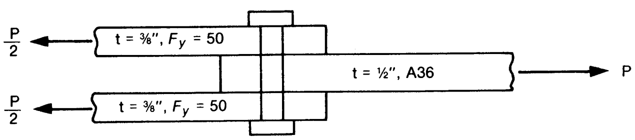

Fig. 8. Double-lap joint

Due to the small net area and lower grade of steel, the middle plate controlled the joint design load. Based on A36 guaranteed minimum yield and ultimate stresses, the allowable design loads per the *Specification* for the four possible failure modes were:

1. Bolt shear (⅞-in. A325-X):
   $P = 36.1$ kips
2. Bolt bearing on plate:
   $P = 1.5\ (58)(7/8)(0.5) = 38.1$ kips
3. End distance:
   $$P = \frac{3(58)\ (0.5)}{2} = 43.5 \text{ kips}$$
4. Plate tension:
   $P_{gross} = 0.6(36)(0.5)(3) = 33$ kips
   $P_{net} = 0.5(58)(0.5)\ [3 - (7/8 + 1/16 + 1/16)]$
   $= 29$ kips

If this joint were designed to serve as a slip critical friction-type connection, the slip load would be of major concern. The design load for a ⅞-in. A325 bolt double shear is 21 kips in this case, and this value would have controlled the connection design. Another estimate of the slip load may be computed from the 39,000 lbs. specified pretension force and an assumed slip coefficient of 0.30:

$$P_{slip} = (0.30)(39{,}000)(2) = 23{,}400 \text{ lb.}$$

Each of the 18 test specimens were subjected to a tensile test using a calibrated Tinius-Olsen Super "L" Deflectometer combination as shown in Fig. 1. A chart recorder was used to plot the load-deflection curve for each specimen and the ultimate tensile load was recorded. The strain rate was monitored and kept constant for all the tests at 1/16—⅛-in. per minute per in. of gage length. It should be noted that due to the configuration of the deflectometer for measurement of overall connection deformation, the test deflection reading may have included some slip of the fixture in the tensile machine grips. This also may account for the wide range in slip load for the connections.

RESULTS

A summary of the test results (Ref. 2) is shown in Table 1. All but five of the specimens were tested to failure of the middle plate. Testing of these five specimens was terminated prior to maximum load for the specimen because loads were approaching or exceeded a safe load limit of 80,000 lbs. for this test apparatus. The first nine specimens were bolted to one fixture and the second nine used the second fixture.

Photographs of representative specimens after testing are shown in Figs. 9–14. A banded plot of load vs. defor-

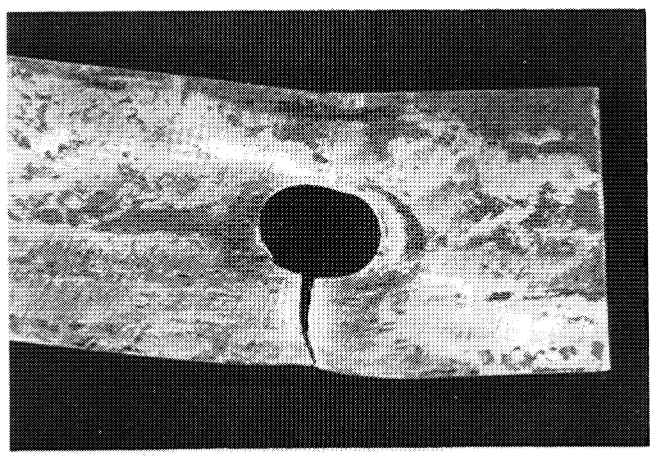

Fig. 9. Hole in Sample P3 after testing, initially made by punching

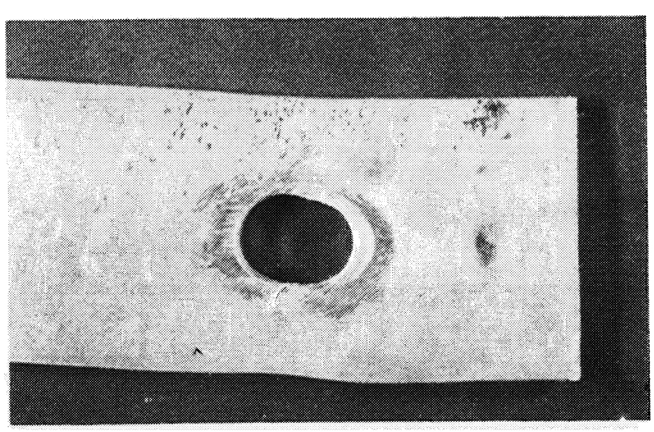

Fig. 10. Hole in Sample P5 after testing, made by punching and grinding burrs

Table 1. Tensile Test Result Summary

Specimen	Ultimate tensile load (lbs.)	Total deflection at ultimate load (in.)	Test number	Final condition	Hole-making technique	Slip load range (kips)
P 1	73,800	1.02	3	Fractured	Punch only	14–22
P 2	76,500	1.05	15	Fractured	Punch only	19–33
P 3	79,500	1.08	9	Fractured	Punch only	20–29
P 4	78,400	1.11	16	Fractured	Punch & grind burrs	22–34
P 5	76,400	1.02	17	Fractured	Punch & grind burrs	41
P 6	77,600	1.02	18	Fractured	Punch & grind burrs	26
P 7	81,000	1.25	10	Fractured	Sub-punch & ream	25–28
P 8	75,300	1.38	11	Fractured	Sub-punch & ream	30–32
P 9	83,900	1.42	12	No breaks	Sub-punch & ream	22–29
P 10	76,400	1.25	7	Fractured	Drill	17–30
P 11	78,900	1.51	2	No breaks	Drill	28
P 12	80,200	1.51	1	No breaks	Drill	26–34
P 13	75,200	1.20	6	Fractured	Flame-cut & ream	25–38
P 14	83,600	1.22	14	No breaks	Flame-cut & ream	20–34
P 15	82,500	1.30	13	Fractured	Flame-cut & ream	19–30
P 16	76,000	1.01	5	Fractured	Flame-cut full size	25–36
P 17	86,300	1.28	8	No breaks	Flame-cut full size	29–41
P 18	78,900	*	4	Fractured	Flame-cut full size	22–28

* Data incomplete

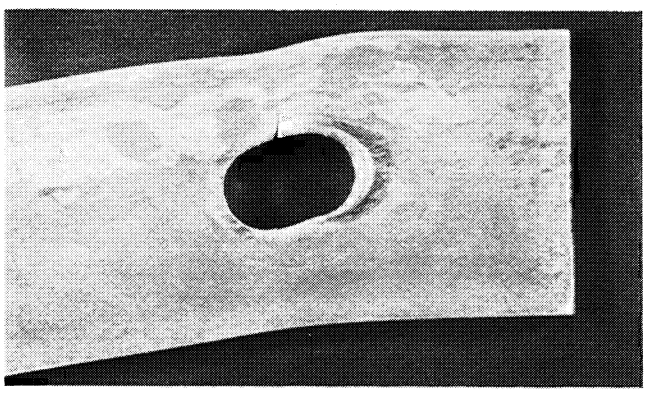

Fig. 11. Hole in Sample P7 after testing, made by sub-punching and reaming

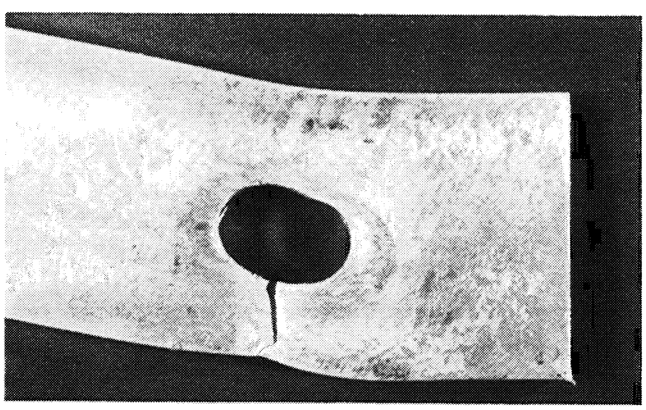

Fig. 12. Hole in Sample P10 after testing, made by drilling

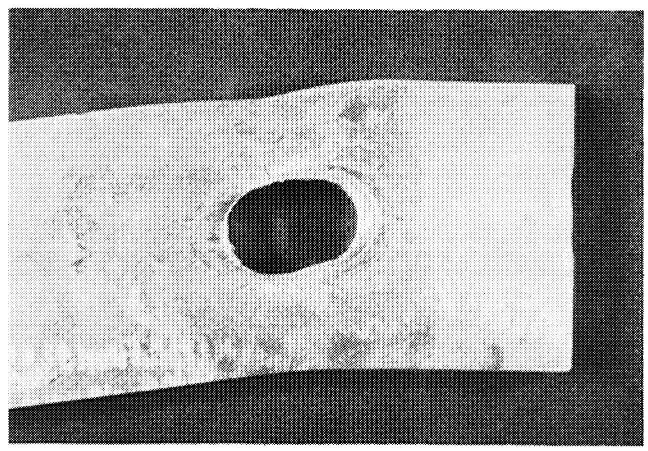

Fig. 13. Hole in Sample P15 after testing, made by flame-cutting and reaming

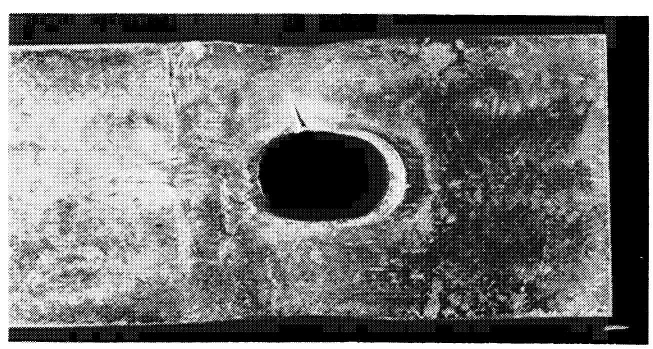

Fig. 14. Hole in Sample P18 after testing, made by flame-cutting

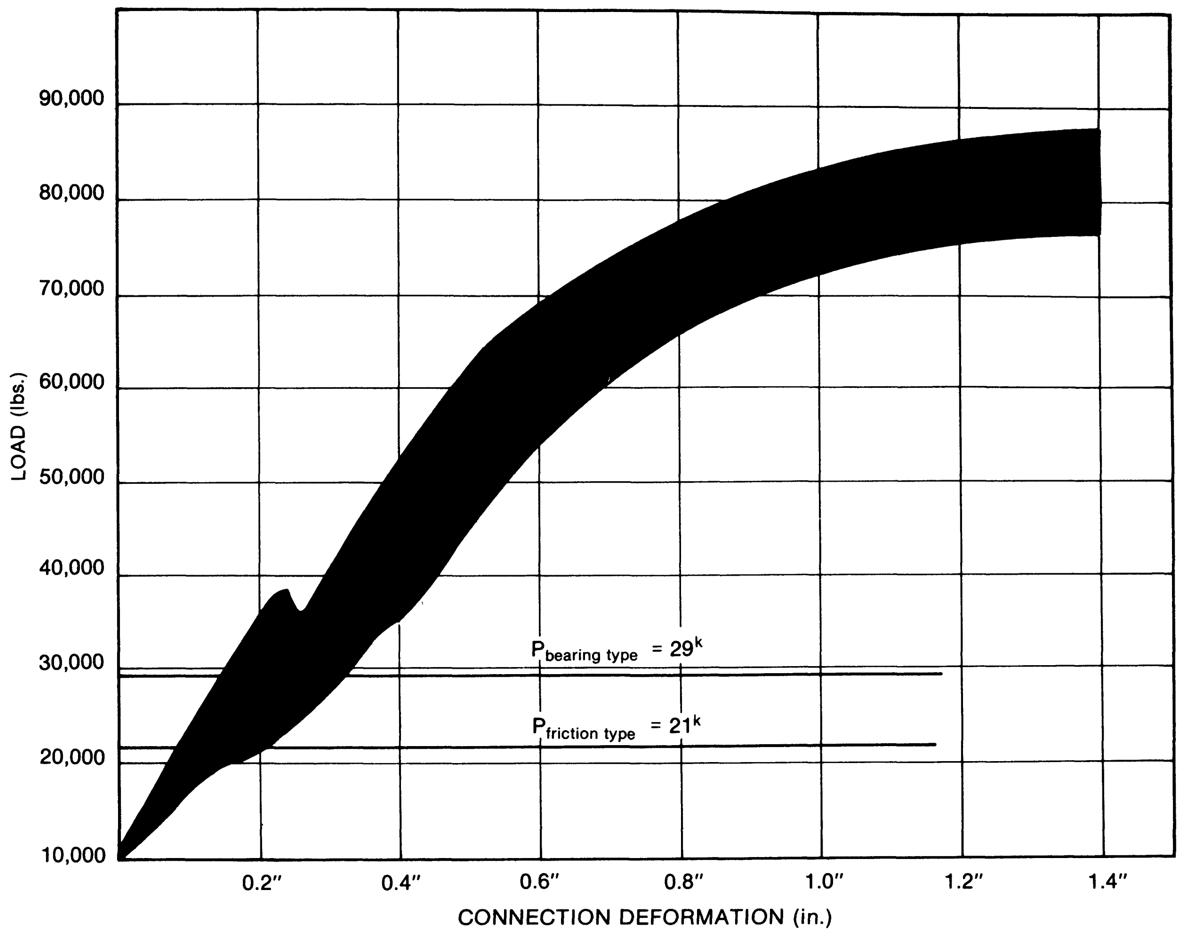

Fig. 15. Banded region of experimental results

mation is exhibited in Fig. 15. It should be noted that all the test results fall within the relatively narrow bounds shown with no dramatic difference in performance. The ultimate strength of the connections is well above (more than two times) the previously computed AISC allowable design load. To minimize the effects of test fixture slippage, the plots were started from a load level of 10,000 lbs. A complete typical load-deformation relationship for a single joint is illustrated in Fig. 16 for specimen P17.

It should be noted that the hole elongation was due not only to bearing deformations, but also to distortion of the net section in tension. Also, as expected, the bearing of the bolt did produce a smooth hole surface. The strength of punched hole connections with and without burrs was not significantly different.

Table 2 summarizes the average ultimate loads for the six specimen groups. Due to the limited sample size, a detailed statistical analysis would not be truly meaningful. Nevertheless, the data presented in Tables 1 and 2 does appear to reflect on a comparative basis:

Table 2. Average Ultimate Loads

Specimen numbers	Hole-making technique	Average ultimate load
P1, P2, P3	Punch	76,600 lbs.
P4, P5, P6	Punch & grind burrs	77,500
P7, P8, P9	Subpunch & ream	80,100
P10, P11, P12	Drill	78,500
P13, P14, P15	Flame-cut & ream	80,400
P16, P17, P18	Flame-cut full size	80,400

Overall average for 18 specimens: 78,472 lbs.

a. That the differences between the average ultimate strengths of a connection fabricated with a particular hole-making procedure and the overall average of all connections is on the order of 5% or less, and
b. That the variability within a given specimen group is approximately of the same order as the variability of the entire sample, and even slightly greater, with a maximum of 7%.

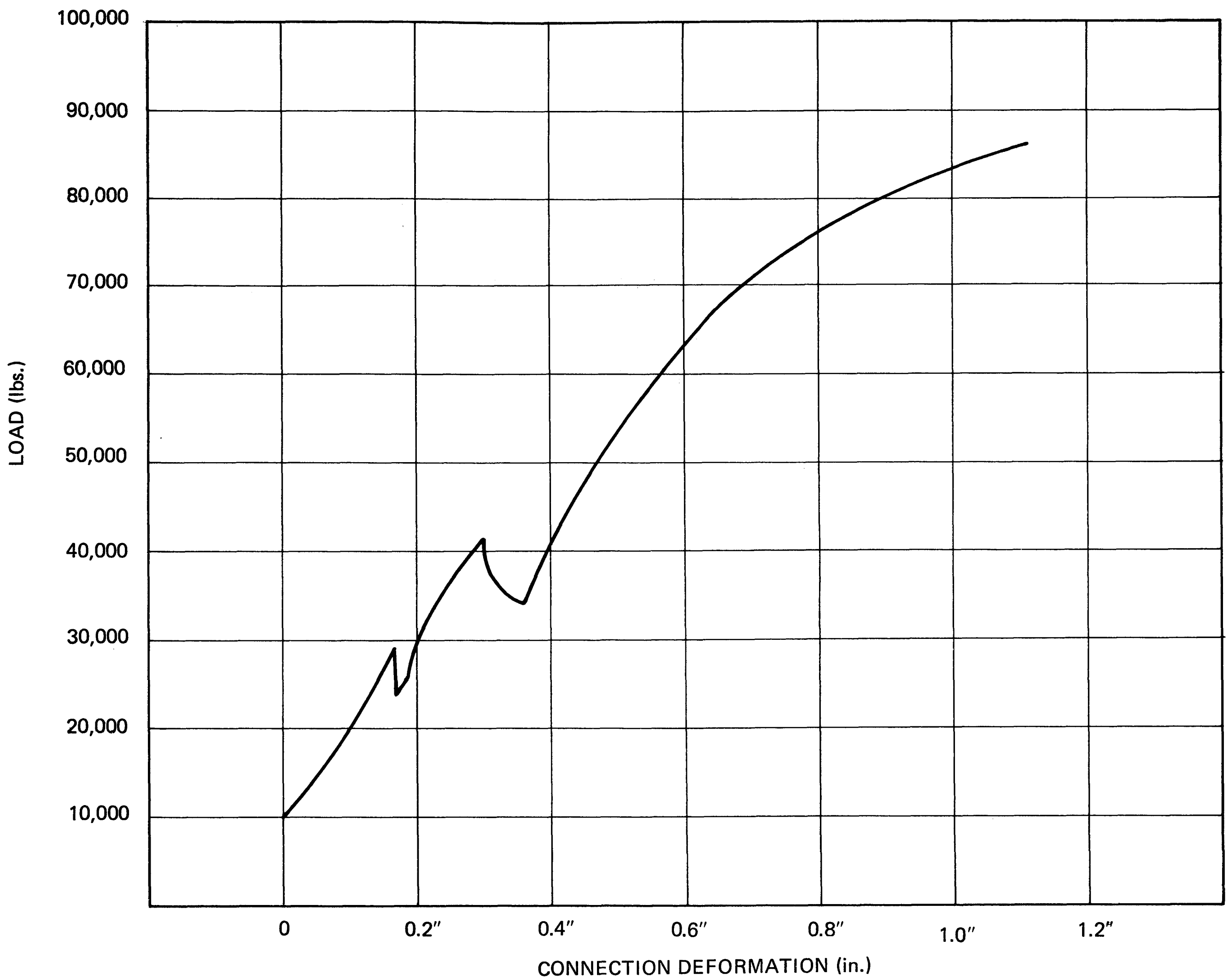

Fig. 16. Typical load-deformation relationship for a single joint, Sample P17

The deformation of the flame-cut and reamed specimens and flame-cut to full size specimens was no less than that for the punched hole specimens and, in several cases, was markedly higher (20–25%).

A standard tensile coupon test was performed on the ½-in. thick A36 material used for the specimens. A standard flat reduced section tensile test specimen was machined from test sample P1 after it had been tested and photographed. This specimen was machined in accordance with ASTM A370 and tested per E8. The result of this testing is shown below.

Tensile strength, psi	82,080
Yield strength, psi (0.2% offset)	53,340
% Elongation	28

In addition to the tension tests, a metallographic examination of the microstructure of the six flame-cut samples, i.e. (P13–P18), was conducted by the testing lab (Ref. 3). Sections were cut along a radius of the $^{15}/_{16}$-in. hole and in a transverse direction to the plate as seen in Fig. 17.

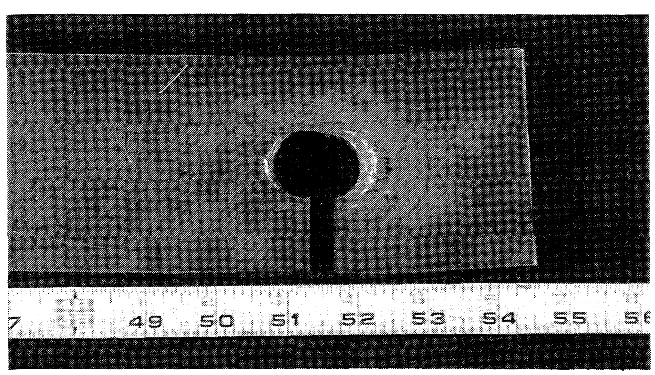

Fig. 17. Test sample area from which metallographic specimen was removed

Each section was mounted in a bakelite mold in a manner which permitted examination of the full thickness of the plate and the flame-cut or reamed surface. Standard metallographic techniques were used to polish each section to a 0.05 micron finish. A metallurgical microscope was used to examine each section at magnification up to 1,000 diameters in both the as-polished and etched conditions. Etching was performed with a solution of 1% Nital to clearly define the microstructure.

At low magnification, samples P13 and P15 displayed almost no evidence of microstructural changes due to flame-cutting (see Fig. 18). Near the outside surface of these two samples, small triangular areas of partially spheroidized pearlite were observed. Both of the triangular areas extended approximately 0.035 in. radially from the hole surface and 0.060 in. normal to the plate surface in the reamed holes. The microstructure of the sample from P14 shows no changes near the flame-cut and reamed hole. Apparently all the material affected by the flame-cutting had been removed by the reaming in this section. No evidence of imperfections was detected in the base metal or the material along the hole wall such as secondary cracks, excessive inclusions, decarburization or laminations.

The flame-cut to full-size samples exhibited a much more apparent change in microstructure, as shown in Fig. 19. The change could be observed along the full thickness of the plate. The heat-affected zone extended farther along the outside surface of one side of the plate than the other. Samples P16, P17, and P18 had heat-affected zones extending 0.19 in., 0.21 in., and 0.20 in., respectively, along one outside surface. Heat-affected material extended 0.05 in., 0.07 in., and 0.06 in., respectively, along the opposite surface.

The microstructures in the flame-cut samples displayed a variety of microconstituents. The base metal was pearlite and ferrite typical of A36 carbon steel plate. As the heat-affected zone was approached, the first changes observed are partial and then complete spheroidization of the pearlite (see Fig. 20). Within approximately 0.04 to 0.07 in., the microstructure became a combination of bainite, martensite, and acicular ferrite. These microconstituents were found along the wall of the flame-cut hole from surface-to-surface.

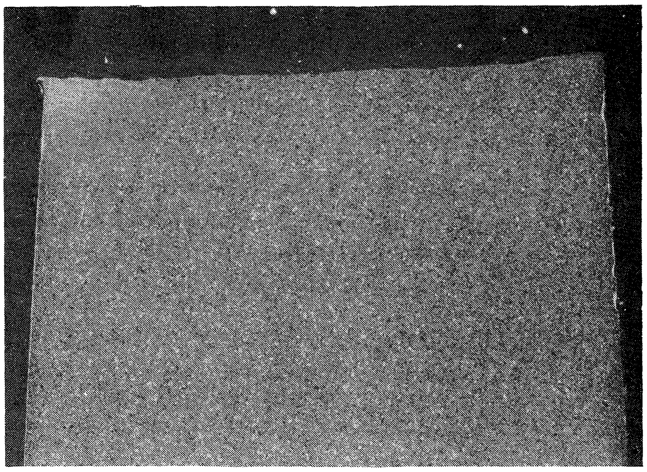

Fig. 18. Typical example of macro appearance of section from Sample P13. Small area of partial spheroidization at upper left. Magnification: 8X. Etchant: 1% Nital

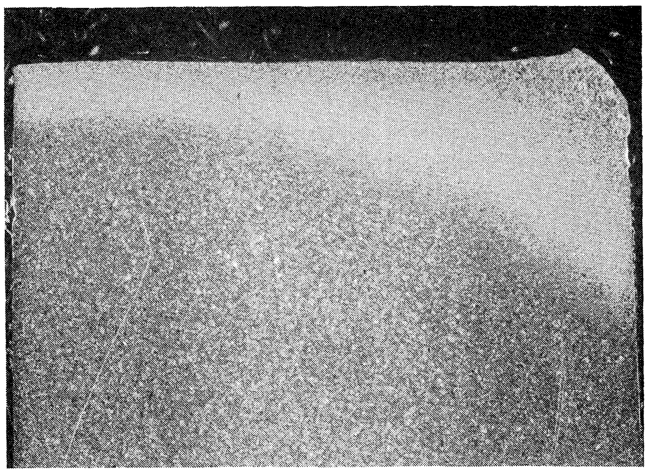

Fig. 19. Example of macro appearance of section from Sample P16. Magnification: 8X. Etchant: 1% Nital

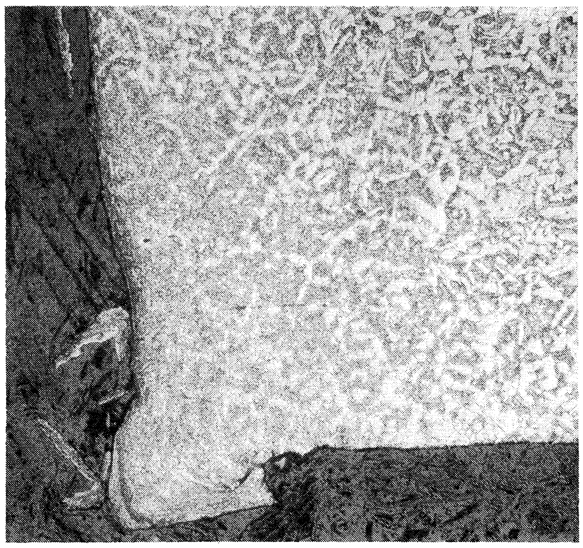

Fig. 20. Partial spheroidization at corner of Sample P15. Magnification: 100X. Etchant: 1% Nital

CONCLUSIONS

The comparison of 18 sample bolted, double-lap joints with standard holes fabricated with six different operations yielded evidence which indicates that there is no significant variation in connection strength correlated to the hole forming method under gradually applied load. The connections performed in a generally uniform manner and the samples appeared quite similar after the test, despite differences in the holes observable before loads were applied. Specifically, evidence that the operation of hole flame-cutting does not adversely affect the connection performance has been obtained.

In considering the results of the tests, one should recognize factors contributing to the uniformity of bolted connections. The friction force of the tightened high-strength bolt distributes a significant portion of the load throughout the area under the head, including material not modified by the fabrication process in the resistance mechanism. Under working stresses, the friction forces will ordinarily be sufficient to prevent connection slip and will reduce stress concentrations whether the connection is viewed as a friction or as a bearing type connection. The only requirement to receive the benefit of bolt friction force at service loads is that the fasteners be pretightened to the specified load. Any roughness caused by thermal cutting would not be expected to affect this load resistance mechanism.

Even though the reported experimental data shows essentially no undesirable structural consequences of flame-cutting in A36 material, the use of this hole-making method is intended as an alternative for special situations, field conditions, and for corrective work. Ordinarily, flame-cutting is not recommended as the primary hole-making method for structural conditions.

One caution must be mentioned relative to the use of hole flame-cutting to full size: workmanship must be of good quality and adhere to procedures appropriate to the materials. Care must be exercised to avoid removing a significant part of the net shear or tension areas.

Though tests have not been conducted to establish allowable tolerances on holes, we recommend the use of a template when flame-cutting holes to full size. The AISC has specified that $\frac{1}{16}$-in. more than the hole diameter be subtracted when determining the net section. If the net area remaining after burning exceeds the required area, reason would dictate that acceptable tolerances have been maintained. The reader is referred to *Quality Criteria and Inspection Standards* Chap. I, Part III, published by AISC, when confronted with questions regarding the acceptability of surface roughness in burned holes.

One question the 18 tests conducted did not address is the influence of thermal cutting of thicker plate material. Whereas the heat-affected zone in the $\frac{1}{2}$-in. thick A36 plates did not reveal significantly embrittled material, this may be more important when flame-cutting thicker pieces.

In our opinion, a good solution to both the workmanship and heat-affected zone issues is to use a cutting torch for piercing a hole in the material (sub-burn) and then reaming to full size. The correct circular hole diameter will thus be achieved with simultaneous removal of most of the possibly embrittled heat-affected material.

In conclusion, a series of tests has demonstrated that the common fabricator hole-making procedures do not significantly affect connection strength and performance under static loads. Furthermore, the prudent utilization of flame-cutting has been shown to be an acceptable alternative.

ACKNOWLEDGMENT

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