Fatigue Resistance of HPS-485W (70 W) Continuous Plate with Punched Holes

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Abstract: Twenty-nine specimens were tested to investigate the fatigue resistance of high-performance steel (HPS-485W) (70 W) continuous plate with punched holes. Specimen thickness, hole diameter, and method used for creating the holes were varied to examine their effect upon fatigue resistance of punched connections utilizing high performance steel. Eight of the 29 specimens were drilled or subpunched and reamed specimens, all of which rated as Category B details. The remaining 21 specimens had punched holes and rated considerably below a Category B. Results from this investigation suggest that current restrictions mandated by some state DOTs concerning punching holes are not overly restrictive when HPS-485W (70 W) is utilized. Performance of drilled and subpunched and reamed specimens met (or exceeded) 2004 AASHTO requirements for Category B details.

DOI: 10.1061/(ASCE)1084-0702(2007)12:1(98)

CE Database subject headings: Bridges; Steel; Fatigue; Drilling; Bolts.

Introduction

High-performance steel (HPS) is increasingly being used for new bridge construction because of its improved properties over conventional structural steel. In particular, ASTM A709 Grade HPS-485W (70 W) has found a niche among designers wishing to capitalize on its high yield strength, increased ductility, toughness, weldability, and improved weathering characteristics. Possessing a higher yield strength than conventional 345 MPa (50 ksi) structural steel, HPS-485W (70 W), has allowed shallower girders to be constructed, leading to both weight savings and increased clearances. A decrease in the carbon content within the chemical makeup of HPS-485W (70 W) has led to increases in toughness and better weldability characteristics. The corrosion resistance of HPS is also an appealing feature, due to reduced life-cycle costs. Currently, over 200 HPS bridges have been designed or constructed in 39 different states (AISI 2004).

While HPS-485W (70 W) is marketed as being more resistant to fatigue than conventional bridge steel, it is currently still held to the same fatigue design standards in AASHTO (2004). It is possible that these standards may be more restrictive than necessary with respect to HPS-485W (70 W), impairing designers' abilities to fully capitalize upon its increased strength. For this reason, it is important that testing be conducted to quantify the fatigue resistance of HPS-485W (70 W). In addition to this, many state DOTs currently do not allow punching of holes in any structural steel primary member greater than 15.9 mm (0.625 in.) thick, instead requiring that the holes be drilled or subpunched and reamed (ODOT 2002; INDOT 1999; MDOT 2003; ILDOT 2002). It is necessary to examine different methods for creating holes to evaluate the current DOT restrictions in lieu of the increased fatigue resistance of HPS-485W (70 W).

As a part of the Federal Highway Association (FHwA's) initiative to use innovative materials in bridge design and construction, the Ohio Department of Transportation (ODOT) has constructed a four-span, five-girder, highway bridge in Lancaster, Ohio, made of HPS-485W (70 W) TMCP. Research concerning that bridge has been ongoing, part of which has focused on adequately characterizing the fatigue properties of HPS-485W (70 W) used in its construction. Because HPS-485W (70 W) appears to demonstrate promise with respect to bridge girder applications, it is important that the behavior of the material, as well as the entire bridge as a structural system, is well understood. This paper focuses on fatigue characteristics of HPS-485W (70 W) bolted splice connections.

Background

A great deal of attention has been devoted to HPS since its development in 1992, but comparatively little work has been done to quantify its performance under fatigue. There is a copious amount of published work mentioning that HPS-485W (70 W) exhibits better fatigue resistance properties than conventional bridge steel does (Wassef et al. 1996; Kulicki 2000; Yakel et al. 1999; Barsom 1997), but little independent experimental work has been performed to support these claims. In addition, there is agreement that "…much is known about the punching of thin plate, due to its application in the automobile industry. However,

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Note. Discussion open until June 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on October 25, 2004; approved on June 14, 2005. This paper is part of the ***Journal of Bridge Engineering***, Vol. 12, No. 1, January 1, 2007. ©ASCE, ISSN 1084-0702/2007/1-98–104/$25.00.

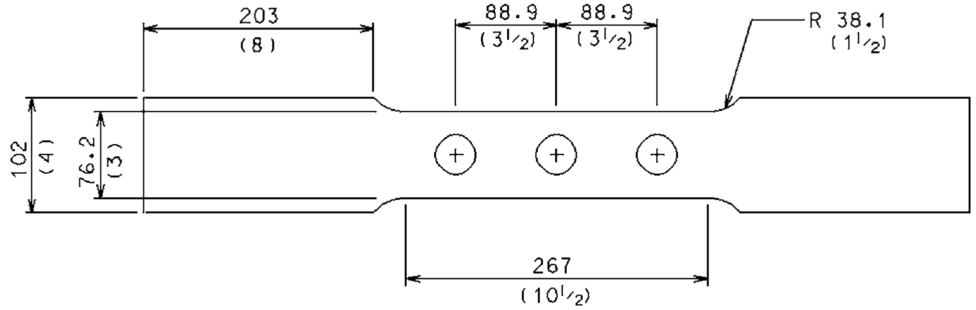

Fig. 1. Dimensions of bolted splice fatigue specimens [mm (in.)]

comparatively little is known about the application of this process in structural steels and its use is heavily restricted by codes and standards in order to avoid the effect of the local damage it produces on structural components" (Sánchez et al. 2004).

A study was performed by Wright (2002), in which fracture tests were performed on full-scale HPS-485W (70 W) I-girders. The girders were cyclically loaded until fatigue cracks formed, upon which they were cooled to −34.0°C (−29.2°F), and then finally were subjected to a design overload. The HPS-485W (70 W) test girders were able to carry the overload until approximately 50% of the tension flange was lost, corresponding to net section stress levels exceeding yield before failure. This result compared favorably to similar test girders fabricated of Grade 345 (50) steel, which exhibited lower crack-size tolerance and fracture stress levels at approximately 60% of yield on the net section.

Chen et al. (2003) recently performed a study which concluded that "The HPS-485W steel tested provides a significantly higher fatigue limit than conventional structural steels." However, that study did not consider specific connection details, examining only flat sheet-type fatigue specimens. The study compared cyclic and monotonic properties of high performance steel against that of lower strength structural steel (Grade A7). The specimens examined in this study were machined from 6.40 mm (0.250 in.) and 51.0 mm (2.00 in.) HPS plates. Specimens were fatigued under strain amplitudes varying from 0.1 to 0.625%, and failure was considered as having occurred when the tensile load decreased by 50%. Tests were also conducted on 6.40 mm (0.250 in.) ASTM A7 plate as a basis for comparison.

Sánchez et al. (2004) recently conducted an investigation concerning the fatigue behavior of punched structural plates. A notable result from that study included finding that drilled samples exhibited double the fatigue resistance of similar specimens with punched holes, and that crack initiation and propagation occurred ten times faster for punched specimens than for drilled. The researchers also found a strong correlation between crack initiation site for the punched specimens and the region of the hole having the most microstructure disturbance, found at a transition region between the cutting zone at the punched side and the intermediate tearing zone. A final point of interest is that the local damage effect of punched holes can be avoided by using a secondary shot peening internal hole treatment. This method is reportedly able to improve the fatigue performance of the punched structural plates to higher levels than observed for the drilled specimens.

Objectives

One goal of this ongoing research is to explore the fatigue resistance of HPS-485W (70 W) plate with holes, commonly found in steel bridge construction in the form of bolted splice connections. The investigators have chosen to use continuous plate specimens with open holes to conservatively approximate the behavior of bolted splices. To adequately characterize the fatigue properties of this connection configuration it is important that geometric properties of the specimens are considered, including hole diameter, thickness, and surface roughness.

Many state DOTs currently require that material thicker than 15.9 mm (0.625 in.) be drilled or subpunched and reamed rather than simply being punched to create the holes. This mandate may increase fabrication time if the processes are not entirely automated, and it is reasonable to hypothesize that with the increased toughness of HPS and the improved efficiency of punching machines that this requirement may be more conservative than necessary. One goal of this research is to determine if the maximum thickness of 15.9 mm (0.625 in.) for punching is an appropriate upper limit for HPS-485W (70 W).

Experimental Setup

Two large HPS-485W (70 W) TMCP plates were obtained from Bethlehem Steel, one 22.0 mm (0.875 in.) thick and the other 51.0 mm (2.00 in.) thick, for the purpose of fabricating the flanges of the Lancaster bridge girders, and to supply steel for adequate material testing. Gross dimensions of the plates were 1.80 m × 20.4 m × 22.0 mm (6.00 ft × 66.9 ft × 0.875 in.) and 1.80 m × 31.9 m × 51.0 mm (5.90 ft × 105 ft × 2.00 in.). The two large HPS plates were cut into multiple smaller plates, from which the bridge girder flanges were cut. Twenty nine fatigue specimens were machined from the remaining steel.

The fatigue specimens all had similar edge dimensions, which are shown in Fig. 1. These specimens are considered a Category B detail by AASHTO (2004). Plate thickness, hole diameter, and method of hole creation were varied to examine the effects of differences in geometry and hole creation processes on the fatigue strength of the specimens. Details for each specimen are shown in Table 1. Each specimen had three holes along the length of the reduced section, with each of the holes produced by one of three hole creation processes: punching, drilling, or subpunching and reaming. The plates were machined from their initial thickness to their final thickness before the holes were made.

Each fatigue specimen was tested at a stress range of either 110 MPa (16.0 ksi) or 158 MPa (22.9 ksi). The first stress range of 110 MPa (16.0 ksi) was chosen as it is the constant-amplitude fatigue threshold (infinite life stress range) for a Category B detail. Six of the 29 specimens were tested at this stress range, all having punched holes. The second stress range of 158 MPa (22.9 ksi) was chosen as it corresponds to a 1,000,000 cycle fa-

Table 1. Bolted Splice Fatigue Specimen Descriptions

Test ID	Hole diameter [mm (in.)]	Thickness [mm (in.)]	Hole	Target stress [MPa (ksi)]
1	23.8 (0.938)	15.9 (0.625)	Punched	165 (23.9)
2	23.8 (0.938)	19.1 (0.750)	Punched	158 (22.9)
3	23.8 (0.938)	22.2 (0.875)	Punched	158 (22.9)
4	27.0 (1.06)	15.9 (0.625)	Punched	158 (22.9)
5	27.0 (1.06)	19.1 (0.750)	Punched	158 (22.9)
6	27.0 (1.06)	22.2 (0.875)	Punched	158 (22.9)
7	30.2 (1.19)	22.2 (0.875)	Punched	110 (16.0)
8	27.0 (1.06)	25.4 (1.00)	Punched	158 (22.9)
9	27.0 (1.06)	25.4 (1.00)	Drilled	158 (22.9)
10	27.0 (1.06)	25.4 (1.00)	Punched	110 (16.0)
11	30.2 (1.19)	15.9 (0.625)	Punched	158 (22.9)
12	30.2 (1.19)	15.9 (0.625)	Reamed	158 (22.9)
13	30.2 (1.19)	19.1 (0.750)	Punched	158 (22.9)
14	30.2 (1.19)	19.1 (0.750)	Reamed	158 (22.9)
15	30.2 (1.19)	19.1 (0.750)	Punched	110 (16.0)
16	30.2 (1.19)	22.2 (0.875)	Punched	158 (22.9)
17	30.2 (1.19)	22.2 (0.875)	Reamed	158 (22.9)
18	30.2 (1.19)	22.2 (0.875)	Drilled	158 (22.9)
19	30.2 (1.19)	25.4 (1.00)	Punched	158 (22.9)
20	30.2 (1.19)	25.4 (1.00)	Reamed	158 (22.9)
21	30.2 (1.19)	25.4 (1.00)	Drilled	158 (22.9)
22	30.2 (1.19)	25.4 (1.00)	Punched	110 (16.0)
23	31.8 (1.25)	15.9 (0.625)	Punched	158 (22.9)
24	30.2 (1.19)	15.9 (0.625)	Punched	110 (16.0)
25	31.8 (1.25)	19.1 (0.750)	Punched	158 (22.9)
26	31.8 (1.25)	22.2 (0.875)	Punched	158 (22.9)
27	31.8 (1.25)	25.4 (1.00)	Punched	158 (22.9)
28	31.8 (1.25)	25.4 (1.00)	Drilled	158 (22.9)
29	31.8 (1.25)	25.4 (1.00)	Punched	110 (16.0)

tigue life for a Category B detail, and was calculated using the AASHTO (2004) equation

$$\Delta F_n = \left(\frac{A}{N}\right)^{1/3} \geqslant \frac{1}{2}(\Delta F)_{\mathrm{TH}} \tag{1}$$

where ΔF_n=stress range; A=constant for a given detail defined by AASHTO (2004); N=number of fatigue cycles to failure; and $(\Delta F)_{\mathrm{TH}}$=constant-amplitude fatigue threshold. For a Category B detail, A is 39.3×10^{11} MPa^3 (1.20×10^{10} ksi^3). The equation is an approximation of logarithmic behavior, with the 1/3 factor defining the slope constant for the *S-N* curves. The coefficient of 1/2 on the right hand side of Eq. (1) ensures that when the design stress range is less than half of the constant-amplitude fatigue threshold, the detail will theoretically provide infinite life (AASHTO 2004). Twenty two of the specimens were tested at the 158 MPa (22.9 ksi) stress range, with one specimen (Specimen 1) inadvertently tested at a stress range of 165 MPa (23.9 ksi).

There are two primary approaches to performing fatigue testing. The first approach is to test a number of identical specimens at different stress ranges, allowing the data points to define a curve on an *S-N* diagram. This procedure is suitable when identical specimens are being examined for fatigue strength. The second method, the technique employed in the current study, is to test several different types of specimens at the same stress range. This method is more appropriate for the current investigation because it lends itself to easy comparisons between the different types of specimens. The results for various types of specimens are more likely to stand apart, resulting in more meaningful data presentation.

Fig. 2. Test setup

Each specimen was tested in a MTS 312 universal testing frame having a maximum load capacity of 245 kN (55.0 kips) and containing a 220 kN (50.0 kips) capacity load cell. The fatigue specimens were tested in load control under tension force only, and were preloaded to a lower load (LL) of 2.22 kN (0.500 kips) to ensure that they remained in tension. The upper load (UL) for the tensile range was calculated as

$$\mathrm{UL} = 2.22\ \mathrm{kN}\ (\text{or } 0.50\ \mathrm{kips}) + (\Delta F_n \times A_{\mathrm{net}}) \tag{2}$$

where ΔF_n was either 110 MPa (16.0 ksi), 158 MPa (22.9 ksi), or 165 MPa (23.9 ksi); and A_{net} was taken as the average net area at the three holes. [A_{net} represents the actual average net area of the three holes in each specimen. A factor of 1.59 mm (1/16th in) was not included for damaged area around the holes.] The test setup is shown in Fig. 2. Specimens were loaded sinusoidally at a rate of 2 Hz until either failure or runout was achieved. Crack detection settings were defined in the software controlling the MTS machine to recognize failure, and were kept as precise as possible in order to detect cracks in early stages of formation. The intent of this approach was to cause the machine to cease cycling upon formation of a crack, detected by a stroke limit setting. Runout was taken as approximately 2.3 million cycles, which is approximately the point at which the AASHTO (2004) fatigue design curve for a Category B becomes a straight line. Specimens that reached the runout point were subsequently removed from the test setup.

Bolts were not placed in the three holes due to multiple considerations. First, there was concern that by installing tensioned bolts, localized compression might be introduced into the area surrounding the holes, lessening the effect of fatigue which was

Table 2. Bolted Splice Fatigue Specimen Results

Test ID	Hole	Target stress [MPa (ksi)]	Average net section area $[\text{mm}^2 \times 10^3\ (\text{in.}^2)]$	N, Number of cycles to failure	AASHTO category
1	Punched	165 (23.9)	—	356,823	C
2	Punched	158 (22.9)	1.02 (1.58)	371,914	C
3	Punched	158 (22.9)	1.25 (1.94)	518,587	B′
4	Punched	158 (22.9)	0.767 (1.19)	479,952	B′
5	Punched	158 (22.9)	0.923 (1.43)	377,387	C
6	Punched	158 (22.9)	1.09 (1.69)	240,681	D
7	Punched	110 (16.0)	1.08 (1.68)	953,106	D
8	Punched	158 (22.9)	1.27 (1.97)	361,684	D
9	Drilled	158 (22.9)	1.24 (1.92)	(2,353,874)	RUN-OUT
10	Punched	110 (16.0)	1.25 (1.93)	(2,186,290)	RUN-OUT
11	Punched	158 (22.9)	0.732 (1.13)	454,891	B′
12	Reamed	158 (22.9)	0.720 (1.12)	(2,712,479)	RUN-OUT
13	Punched	158 (22.9)	0.879 (1.36)	392,249	C
14	Reamed	158 (22.9)	0.859 (1.33)	(2,396,323)	RUN-OUT
15	Punched	110 (16.0)	0.896 (1.39)	1,165,808	C
16	Punched	158 (22.9)	1.10 (1.71)	253,772	D
17	Reamed	158 (22.9)	1.05 (1.62)	(2,364,854)	RUN-OUT
18	Drilled	158 (22.9)	1.02 (1.58)	(2,000,000)	RUN-OUT
19	Punched	158 (22.9)	1.20 (1.86)	326,747	D
20	Reamed	158 (22.9)	1.15 (1.79)	(2,232,370)	RUN-OUT
21	Drilled	158 (22.9)	1.18 (1.83)	(2,709,305)	RUN-OUT
22	Punched	110 (16.0)	1.20 (1.86)	59,400	C
23	Punched	158 (22.9)	0.707 (1.10)	489,884	C
24	Punched	110 (16.0)	0.722 (1.12)	1,285,563	C
25	Punched	158 (22.9)	0.849 (1.32)	408,255	C
26	Punched	158 (22.9)	1.05 (1.63)	228,086	D
27	Punched	158 (22.9)	1.16 (1.79)	296,015	D
28	Drilled	158 (22.9)	1.13 (1.75)	(2,410,651) ± 21,750	RUN-OUT
29	Punched	110 (16.0)	1.16 (1.79)	780,143	D

being applied in tension. Omitting the bolts from the test setup was conservative. Second, there has recently been some interest in the fatigue performance of holes in bridge members without bolts. It is not uncommon for bolts that are used for fitup purposes during construction to be removed before the bridge is placed into service, leaving behind empty holes. Fatigue properties for such regions are not well understood. The researchers are currently performing a parallel study on Grade A588 steel to quantify differences between three bolted splice configurations. That study will identify differences between the test setup used in the present study, a similar setup incorporating pretensioned bolts in each of the holes, and another examining plates bolted together in a lap splice configuration.

Results and Discussion

Summary results for the 29 bolted splice fatigue specimens are shown in Table 2. Data have also been plotted on a standard AASHTO (2004) *S-N* diagram in Fig. 3. Each data point was assigned the appropriate fatigue category (A, B, B', C, D, E, or E') by calculating the AASHTO (2004) constant A for each specimen. The calculated constant for each specimen was then compared against the constant designated to each fatigue category. The AASHTO (2004) category with the A value closest below the calculated value was assigned to the specimen. It should be reiterated that the detail under investigation, regardless of hole creation method, is considered by AASHTO (2004) to be a Category B detail. However, many state DOTs do not permit holes to be punched in thicker plates [thickness greater than 15.9 mm (0.625 in.)].

Table 2 and Fig. 3 indicate that the four drilled and the four subpunched and reamed specimens rated as AASHTO (2004) Category B details. These eight specimens were tested at a 158 MPa (22.9 ksi) stress range, corresponding to a predicted failure at 1,000,000 cycles; all of the specimens reached runout and exceeded the calculated prediction. This may imply that there is some notable fatigue performance improvement in a bolted splice connection when HPS-485W (70 W) is utilized. However, it is important to note that the specimens still performed as Category B details. Testing should be performed at a higher stress range to examine if the detail performs at a Category A level when HPS-485W (70 W) is utilized with drilled or subpunched and reamed holes.

Fractures initiated exclusively in specimens having punched holes, and always originated at a hole; only one crack was observed per specimen. The hole experiencing crack initiation (upper, middle, or lower) varied between specimens, and appeared to be random. Crack initiation seemed to be closely tied to the amount of disturbance in the hole surface; in some specimens it was apparent without magnification that the crack originated at a flaw caused by the punching process. In other specimens, the

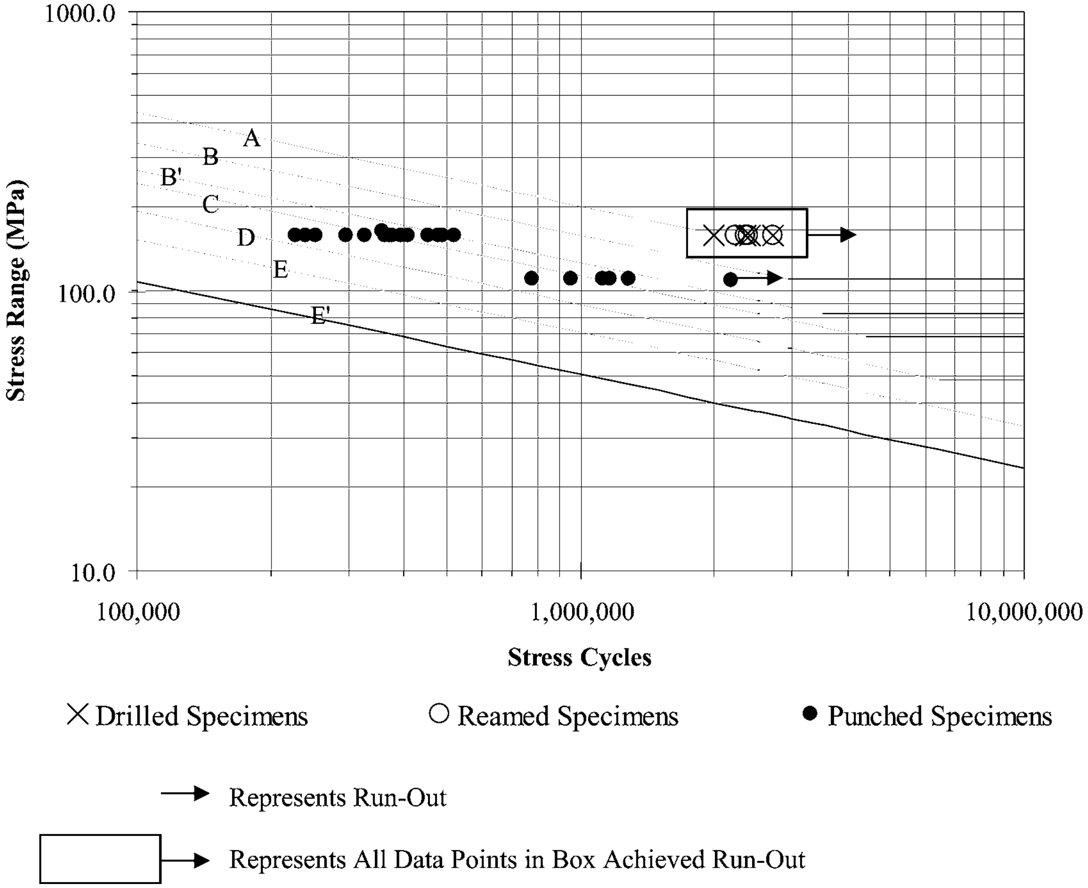

Fig. 3. *S-N* diagram for 29 bolted splice fatigue specimens

crack did not occur at the widest part of the hole (midheight), suggesting that a flaw instigated fracture. A picture of the failure plane for Test ID No. 3 is shown in Fig. 4, and is fairly typical of all punched specimens examined in this study.

The 21 specimens having punched holes rated considerably below an AASHTO (2004) Category B detail. One of the punched specimens (5% of the specimen sample set) reached runout, three (14.3% of the sample set) rated as Category B′, nine (43%) as Category C, and eight (38%) as Category D. Five of the six punched specimens tested at 110 MPa (16.0 ksi) failed to achieve runout, and only one was considered to have attained runout. None of the 15 punched specimens tested at or near 158 MPa (22.9 ksi) reached 1,000,000 cycles. The average result for the 21 punched specimens revealed a rating between AASHTO (2004) Category C and D. The results for the punched specimens suggest that any improvement in the fatigue performance of HPS-485W (70 W) over that of conventional structural steel does not warrant lifting current DOT restrictions on punching holes in thicker plate. These restrictions are in place to ensure a certain level of quality in hole finish, necessary because of practical considerations.

There are some practical limitations to punching holes in thicker plate. As plate thickness increases it becomes more difficult for holes to effectively be punched to size. The quality of the hole diminishes with thicker plate and the likelihood of the part becoming bent also increases. Tool parts dull more quickly, adding to overall machine expense and maintenance, and also detracting from the quality of the finished part. Every defect in a hole becomes a location for a potential crack to begin forming under fatigue. Sánchez et al. (2004) performed research which examined where fatigue cracks were likely to originate with respect to damaged "zones" in punched holes.

While the study performed by Sánchez et al. (2004) did not consider different plate thicknesses, a distinction was made defining three regions around holes after punching. Those three zones were defined as Zone One, where shear is made by contact with the punch and the hole exhibits low surface roughness; Zone Two, where there is significant tearing of the material, great surface damage, plasticization, and possible crack initiation; and Zone Three, where shear is made by contact with the die and the hole exhibits low surface roughness. From this, it seems reasonable that Zone Two might be larger for holes punched in thick plate than in thin plate. If this is true, then there is inherently more surface area with high levels of damage and tearing in a hole punched through thick plate than there is in a hole punched through thin plate. This hypothesis is supported by the current work discussed in this paper. The work done by Sánchez et al. (2004), however, did not examine the effect of other geometric properties such as plate thickness and hole diameter.

Due to the nature of punching, it is of interest to examine the data with respect to the geometric properties of the specimens. As mentioned earlier, the hole thickness and hole diameter were varied between specimens to investigate the possibility of the presence of a relationship between the two parameters. To examine the effect of hole diameter and plate thickness on the fatigue strength of a HPS-485W (70 W) bolted splice, the diameter to thickness ratio (D/t) was calculated for each specimen. The constant A, found in the AASHTO fatigue life equation [Eq. (1)] and linked directly to fatigue life, was calculated for each specimen using Eq. (1). The ensuing data were plotted against the D/t ratios

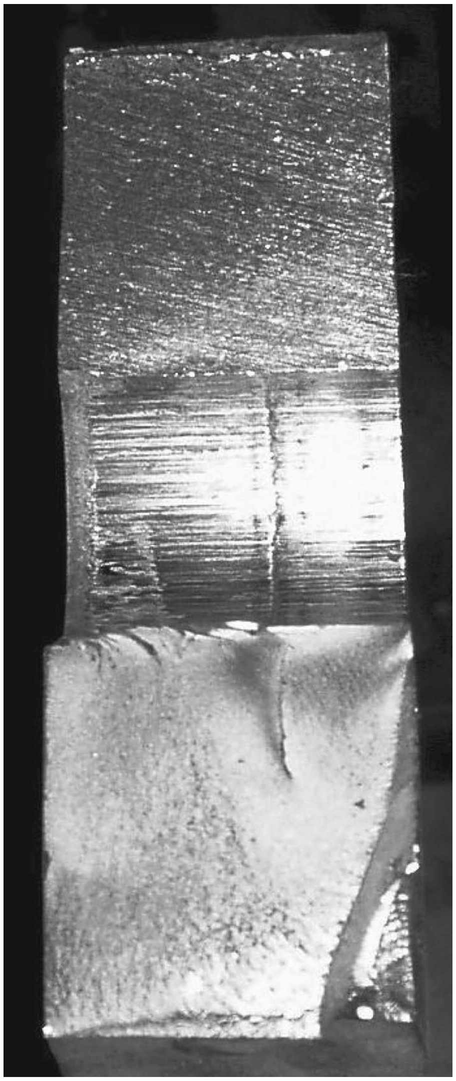

Fig. 4. Fracture surface for Test ID No. 3

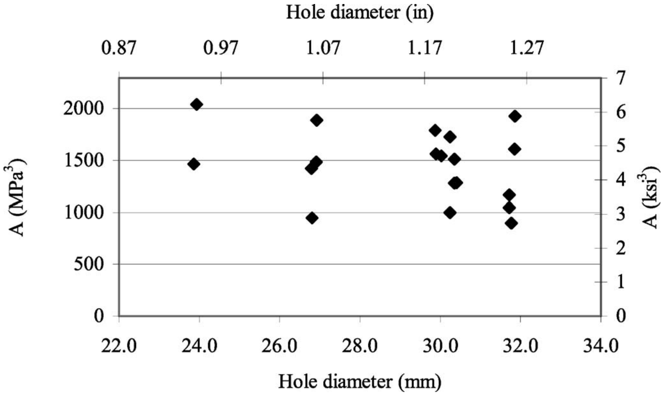

Fig. 6. *A* versus hole diameter

to gain a sense of the impact of the ratio on fatigue life for this connection type. The resulting graph is shown in Fig. 5 and the plot suggests that this connection performs better under fatigue with an increasing D/t ratio. To examine whether the hole diameter or the plate thickness had a greater effect upon the fatigue performance, each of these values were separately plotted against A. It was found that there was very little correlation between hole diameter and A (Fig. 6). There was some minor correlation between plate thickness and A (Fig. 7). This might suggest that the better fatigue performance seen in specimens with higher D/t ratios was more dependent upon plate thickness than hole diameter. However, it should be noted that the only truly notable correlation found to exist was the A versus (D/t) relationship.

There is one data point (Test ID No. 3) seen in each of the above-mentioned plots that could be interpreted as an outlier. Interestingly, this punched specimen exhibited significantly greater fatigue resistance than other punched specimens. Punched specimens tested at 158 MPa (22.9 ksi) achieved an average of 370,462 cycles. Test ID No. 3 reached 518,587 cycles—approximately 40% more than the average. This specimen was left in the data pool since no specific reason for its longevity could be identified. A visual inspection revealed that it did not have significantly less damage to the holes than other punched specimens. The fracture surface for this specimen is shown in Fig. 4.

Another variable affecting fatigue life considered was surface roughness of the holes. Each hole was visually and tactilely inspected and then classified using a comparator surface finish scale. The results were examined with respect to the fatigue life of each specimen, but no correlation was found to exist. It is possible that with the use of a more sensitive instrument a relationship between surface roughness and fatigue life could be identified. Pictures shown in Fig. 8 show the difference in hole quality between the punched, drilled, and subpunched and reamed hole types.

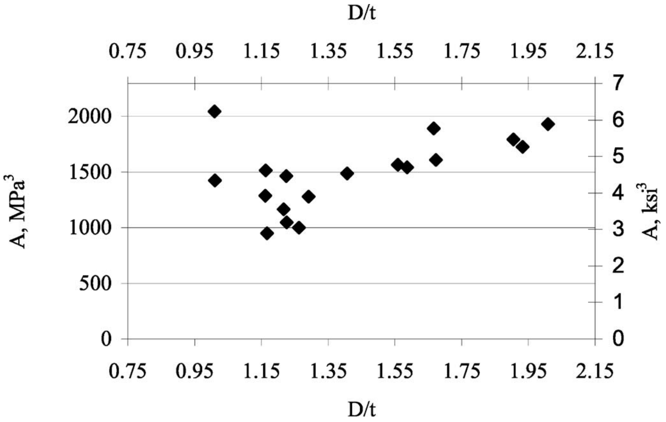

Fig. 5. *A* versus diameter-to-thickness ratio

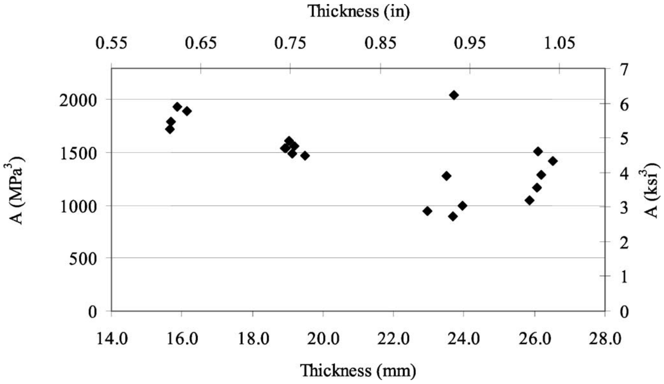

Fig. 7. *A* versus plate thickness

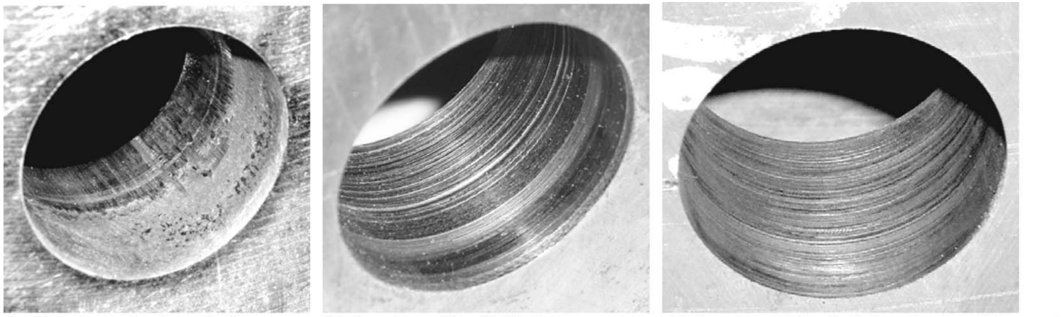
(a) Specimen 5 – Punched *(b) Specimen 28 - Drilled* *(c) Specimen 20 – Sub-Punched and Reamed*

Fig. 8. Different hole types

Conclusions

The HPS-485W (70 W) drilled and subpunched and reamed specimens rated at or above AASHTO (2004) Category B details, while the punched specimens rated between a Category C and D. This leads to conclusions that:

1. Current provisions mandated by many state DOTs restricting punching holes in thicker plate are justified;
2. A trend exists which suggests that fatigue resistance increases with increasing diameter to thickness ratio; and
3. Current AASHTO (2004) fatigue design specifications appear to be applicable to HPS-485W (70 W) in this configuration.

Overall, the HPS-485W (70 W) continuous plates with drilled and subpunched and reamed holes exhibited fatigue resistance at least as good as is required by AASHTO (2004), and in many cases, slightly better. This finding reinforces the applicability of HPS-485W (70 W) to bridge girder applications.

Acknowledgments

The writers would like to acknowledge the Ohio Department of Transportation (ODOT) and the Innovative Bridge Research and Construction (IBRC) program sponsored by the Federal Highway Administration (FHwA) for their ongoing cooperation and funding of this project. They would also like to recognize Stupp Bridge for their help in fabrication of the specimens and Peddinghouse Corp. for their help punching the specimens.

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