TECH**BRIEF**

Optimization of Grade 100 High-Performance Steel Butt Welds

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Introduction

The development of high performance steels (HPS) began in the early 1990s as a result of cooperation between the Federal Highway Administration (FHWA), the U.S. Navy, and the American Iron and Steel Institute (AISI). Out of the extensive research performed, three new weathering grades of HPS were created that had minimum yield strengths of 50, 70, and 100 ksi. These are referred to as HPS50W, HPS70W, and HPS100W. All three are represented in the American Society for Testing and Materials (ASTM) A709 "Standard Specification for Structural Steel for Bridges" material specification.(1)

In the development of the HPS grades, three advisory groups were formed to oversee and guide the development of the steels in terms of their design, welding, and corrosion aspects. One of the aspects considered by the Welding Advisory Group (WAG) was how to butt splice HPS100W plates together without matching strength consumables. At the time the research began, matching 100-ksi-yield weld consumables were available but were also much more expensive than typical welding consumables for steel bridge fabrication. Therefore, the WAG wanted to demonstrate the use of "optimized" welding as a potentially useful option for the HPS steels under certain circumstances. Optimized welding harnesses triaxial internal constraint, which wider and thicker plates can use to develop through-thickness stresses and demonstrate an apparent increase in yield strength. Therefore, for particular combinations of joint width and thickness, an undermatched weld consumable could develop strengths equivalent to matching consumables. In this case, the "joint" is the butt splice between two different plates. Optimized welding is an attractive option in welds joining HPS plates of differing strength or when weld consumables match the HPS steel in terms of toughness but not in strength. Matching or overmatching welds are not necessary when optimization can be achieved.

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This TechBrief reports the results from two final tests in this overall research project. However, the results from the prior tests published in references 3, 4, and 5 will also be included in order to present the full circle of findings. The work published in references 3, 4, and 5 was the result of funding provided by the WAG (from FHWA, AISI, and the Navy) along with some supplementary funding by the Pennsylvania Technology Alliance.

Review of Previous Tests

The original selection of the joint width-to-thickness ratios in this research was based on the original work of Satoh and Toyoda first published in the September 1975 Research Supplement of the *Welding Journal.*(2) They proposed the use of undermatched welds in structures. Their research suggested that an undermatched weld in a plate with a minimum width-to-thickness ratio of seven would perform like a fully matched one because it was "optimized" due to triaxial internal constraint developed under stress. However, this proposal was predicated on the assumption that the plates were relatively thick and the ratio of weld strength to that of the plate was about 85 percent or greater.

Description of Specimens

In total there were 14 large pull-plate specimens used to determine the optimal width-to-thickness (W/T) ratios of HPS70W and HPS100W plates. HPS50W was not included in the testing because matching consumables are readily attainable at that strength level. The geometry of the pull-plates in figure 1 shows that the overall length of the specimens was just over 11.5 ft. The 14 specimens were made from 6 different parent plates and 11 different weld consumables. The yield strength, tensile strength, and elongation for each of the materials are shown in table 1. The reported values are averages if replicates were tested. The chemical compositions of the individual plates and welds are shown in table 2.

The combinations in which the individual plates and welds were used to develop the pull-plates will be listed in the next section. The cross-sectional area of the pull-plates ranged from 6.45 to 25.5 inches^2 and, considering the strength of the base metals, required a testing machine capable of at least 2,500 kips in tension.

Figure 1. Schematic of pull-plate specimens (units = inch).

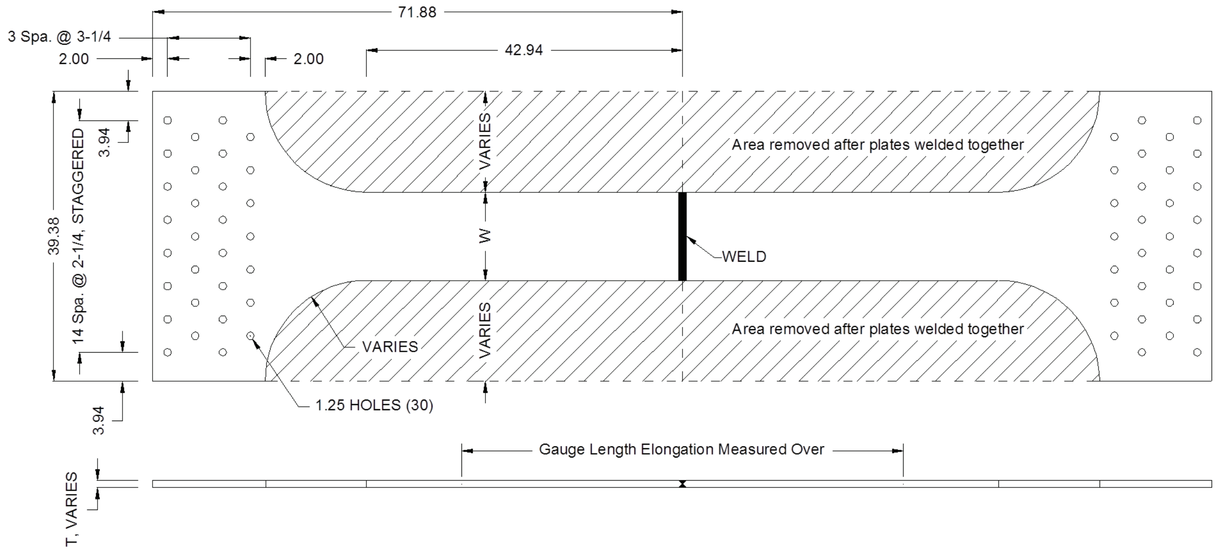

Table 1. Material Properties of Specimen Plates and Welds. (3,4,5)

Material	Name or Type	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (percent)
P1	HPS70W	82.8	97.1	26.7
P2	HPS70W	75.0	98.0	25.0
P3	HPS100W	100.5	113.5	22.0
P4	HPS100W	102.5	114.5	23.5
P5	HPS100W	105.0	117.0	24.0
P6	HPS100W	114.5	122.5	21.5
W1	SAW	95.9	104.6	28.5
W2	SAW	60.8	77.7	34.3
W3	SAW	68.0	85.0	29.5
W4	SAW	112.5	117.5	22.5
W5	SAW	95.0	109.5	27.5
W6	SAW	79.5	91.0	26.5
W7	SMAW	66.2	78.5	29.1
W8	FCAW	91.5	98.5	27.5
W9	GMAW	91.2	96.7	21.0
W10	GMAW	92.7	98.0	22.5
W11	GMAW	104.5	110.5	22.5

SAW = Submerged Arc Welding
SMAW = Shielded Metal Arc Welding
FCAW = Flux Cored Arc Welding
GMAW = Gas Metal Arc Welding

Table 2. Chemical Composition of Specimen Plates and Welds. (4,5)

Ma	Element Composition (percent by weight)										
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Al
P1	.091	1.26	.017	.008	.37	.30	.56	.10	.06	.30	.016
P2	.081	1.22	.010	.005	.37	.30	.51	.06	.06	.38	.033
P3	.066	1.00	.011	.010	.27	.77	.51	.49	.06	1.05	.034
P4	.062	.93	.007	.010	.28	.73	.51	.46	.06	.96	.030
P5	.053	.94	.006	.009	.27	.71	.50	.45	.06	.92	.013
P6	.057	1.30	.009	.002	.25	.72	.49	.46	.07	1.02	.042
W1	.070	1.47	.013	.006	.37	1.74	.06	.35	.01	.11	.008
W2	.076	1.12	.021	.009	.56	1.06	.11	.05	.01	.11	.006
W3	.094	1.13	.026	.011	.57	.82	.11	.07	.02	.23	.013
W4	.058	1.49	.008	.006	.34	2.32	.27	.28	.01	.07	.008
W5	.075	1.18	.007	.005	.27	.94	.35	.24	.05	.85	.020
W6	.074	1.03	.018	.011	.41	.88	.28	.29	.04	.63	.021
W7	.056	1.03	.010	.015	.45	.04	.07	.05	.01	.11	.001
W8	.054	1.11	.010	.011	.30	1.90	.07	.09	.03	.09	.005

Results

Table 3 outlines all the critical results from the 14 pull-plate tests. Tests 13 and 14 are the results from the most recent tests sponsored by FHWA. These two specimens were tested because the prior testing could not optimize a 1-inch-thick plate of HPS100W, and the optimization point was desired. Within this table are the relevant geometric parameters of the specimens, the weld-to-plate (W/P) yield and tensile strength ratios, the test-to-plate (T/P) yield and tensile ratios, the elongation of the specimen, and whether the specimen was considered optimized or not. The T/P ratio compares the yield and tensile strength in the welded specimen to that from the material test of the plate alone. In this case, the yield from the welded specimen test uses a 0.2 percent offset method to define the yield stress. Unless otherwise noted, failure always occurred in the weld.

The two "control" specimens had standard overmatched weld strengths where the tensile strength of the weld exceeded that of the plate. It is a characteristic of optimized welds that they fail in the weld joint. This may seem to be undesirable or even unsafe to some, but it is the overall performance of the weldment that is important, not where final failure occurs. If a plate is stressed over its yield strength, welded or not, it will begin to plastically deform. When it reaches its tensile strength, it will rupture. The most important characteristic of an optimized weld joint is that it does not begin to plastically deform until the plate yield strength is reached or fracture until the plate tensile strength is reached, respectively. In order to avoid premature fracture, however, there must also be some overall ductility associated with the failure, so a minimum ductility criterion is also necessary and arbitrarily selected as 5 percent over a 60-inch gauge length. While the 5 percent strain criteria may seem small compared to base metal requirements, localized strain measurements on a smaller gauge length around the welds were typically observed to be around 25 percent. Therefore, the specimen was considered optimized if both the T/P yield and tensile ratio exceeded 1 and the plate had an elongation of 5 percent or more over the 60-inch gage length.

Table 3. Results of All HPS Optimization Tests. (3,4,5).

	Test	Plate and Weld	Plate Thickness (inch)	W/T Ratio	W/P Yield Ratio	W/P Tensile Ratio	T/P Yield Ratio	T/P Tensile Ratio	Elongation in 60 inches (percent)	Optimized?
HPS70W	1	P1 W1	1.5	16	1.16	1.08	1.00	1.00	12.2	Control[1]
	2	P1 W2	1.5	16	0.73	0.80	1.00	1.00	6.7	Yes
	3	P1 W2	1.5	16	0.73	0.80	1.00	1.00	7.4	Yes
	4	P1 W7	1.5	16	0.80	0.81	1.00	1.00	6.5	Yes
	5	P2 W3	1.5	7	0.91	0.87	1.05	0.96	6.0	Yes
	6	P2 W3	1.5	3.33	0.91	0.87	1.03	0.91	4.0	No
HPS100W	7	P3 W4	1.5	7	1.12	1.04	1.01	1.00	8.6	Control[1]
	8	P3 W5	1.5	7	0.95	0.96	1.02	1.00	8.5	Yes
	9	P3 W6	1.5	7	0.79	0.80	1.00	0.94	2.5	No
	10	P4 W8	1.5	7	0.89	0.86	1.00	0.97	3.2	No
	11	P4 W9	1.5	7	0.89	0.84	0.99	0.95	2.6	No
	12	P5 W10	1	7	0.88	0.84	1.00	0.92	0.8	No
	13	P6 W11	1	12	0.91	0.90	0.99	0.95	2.4	No
	14	P6 W11	1	16	0.91	0.90	0.98	0.98	1.4	No

Tests 1 through 6 used HPS70W plate material. Indeed, weld optimization was achieved with a W/T of 7 or greater but was not optimized at a W/T of 3.33. Therefore, a truly optimized W/T ratio would be somewhere between 3.33 and 7, confirming the work of Satoh and Toyoda. Note that test 5 was classified as optimized despite the T/P ratio not exceeding 1. This was a judgment call because this specimen achieved very good ductility on the same order as the other optimized tests. Optimization was achieved at W/P yield and tensile ratios of 0.91 and 0.87, respectively, at W/T of 7. When the W/T was increased to 16, the W/P yield and tensile ratios were as low as 0.73 and 0.80, respectively.

Working under the presumption that 1.5-inch-thick HPS70W plates with W/T of 7 could be optimized, the same dimension tests were run with HPS100W plates (tests 7 through 11). Tests 7 and 8 were welded with the submerged arc process. While test 7 was the overmatched strength control, optimization was achieved using an undermatched filler for test 8 with W/P yield and tensile ratios in excess of 0.95. Tests 9 through 11 were welded with three different processes, and optimization could not be achieved even with W/P ratios as high as 0.89. Therefore, it was determined that the welding process was not a key variable; the more important factor was the W/P ratio.

In the HPS70W plate tests, there was also some evidence that the absolute width may also play a role in the optimization process. In particular, tests 4 and 5 were optimized, though the one with lesser width (test 5) had reduced T/P tensile ratio over test 4, despite the W/P ratios being higher. The role of absolute thickness was also investigated with a 1-inch-thick HPS100W plate in test 12. The performance of test 12, both in strength and ductility, was not as good as with the equivalent thicker plate in test 11. This further reinforces the idea that optimized welds attain their strength and ductility from triaxiality, which increases with thickness and width.

Using a 1-inch-thick HPS100W plate at a W/T ratio of 7 does not represent realistic dimensions of a girder flange splice. This led to tests 13 and 14 using an HPS100W plate with a higher W/T ratio to create a more realistic width of a girder flange splice. Tests 13 and 14 investigated a

1-inch-thick HPS100W plate at W/T ratios of 12 and 16 in the hope of creating more triaxiality. None of these tests achieved optimization, failing both criteria and even having W/P ratios in excess of 0.90.

Conclusions

The completed phases of the research on optimized welding of butt welds with HPS70W plates demonstrated that when undermatched weld metals are used in these joints, they can perform satisfactorily. This can be accomplished provided that the W/T ratio is 7, the W/P yield ratio is 0.91 or greater, and the W/P tensile ratio is 0.87 or greater. This means that 60 ksi electrodes could be used to join HPS70W tension butt splices, provided that the joint geometry meets these requirements. For W/T ratios higher than 7, the W/P ratios could be relaxed.

Unlike the HPS70W plates, the 1.5-inch-thick HPS100W plates could not be optimized unless the weld metal yield and tensile strengths were 0.95 times that of the plate and the W/T ratio was 7 or greater. Until further research can justify, tension butt splices of HPS100W will likely continue to require matching electrodes. Use of undermatched electrodes would rely on qualification to ensure that the W/P ratios are 0.95 or greater.

None of the 1-inch-thick HPS100W specimens could be optimized, but this research could not definitively identify whether this was a thickness dependence or because the W/P strength ratios were not 0.95 or greater. It is likely more an effect from the plate being so thin that through-thickness constraint cannot develop, hence reduced triaxiality. For this reason, careful consideration should be given when trying to optimize welds of plates less than 1.5 inches thick.

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