Experimental Study of the Static Properties of Q690GJ High Performance Structural Steel

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***Abstract*—The application of high-strength steel in steel structures is conducive to reducing the amount of steel used and the weight of the structure, but the increase in steel strength also results in a higher flexural strength ratio and to a certain extent a lower ductility, which is not conducive to the application in the field of building structures. In this study, a series of monotonic tensile tests were carried out on the new high-performance seismic structural steel developed by HISCO to analyse the static mechanical properties of the base material and butt welds at different plate thicknesses, different thickness delamination positions and different sampling directions. The results show that the new steel has a high strength while maintaining a low flexural strength ratio, which satisfies the requirements of the Code for Steel Plates for Structural Use in Buildings and can be used in building structures with special requirements for steel strength. 45mm steel plate mechanical properties at different thicknesses meet the distribution pattern of gradually decreasing strength and increasing ductility from both sides of the surface to the middle layer.**

***Keywords*—high-performance structural steel, thick steel plate, welded specimen, static properties, stress-strain curve**

I. Introduction

To investigate the difference in properties of high strength steels compared to normal strength steels, Dai *et al.* [1] studied and compared the mechanical properties of Q460 steel and Q345 steel and found that in addition to being stronger, Q460 steel was no weaker than conventional Q345 steel in terms of ductility and energy dissipation capacity. In order to investigate the mechanical properties of higher strength structural steels, Lu [2] and others carried out monotonic and cyclic loading tests on 690 MPa high-construction steels and found that the stress-strain curve of Q690GJ steel did not have a significant yield plateau under monotonic loading, in addition, a large number of scholars have conducted experimental studies on the mechanical properties of conventional high-strength steels [3, 4]. However, most conventional high-strength steels have only a single strength advantage and lack the functional requirements to meet the needs of the construction industry in complex environments. Conventional high-strength low-alloy steels (HLSA steels) have a significant increase in flexural strength ratio as the strength grade of the steel increases. However, many domestic and international steel standards and steel design codes specify limits for the mechanical properties of steel, most of which are between 0.80 and 0.85 [5], and China's GB/T 19879 [6] requires a flexural strength ratio of ≤0.85 and an elongation after break of ≥14% for 690 MPa steel for building structures.

HISCO's newly developed 690 MPa high performance structural steel has higher ductility and lower flexural strength ratio than existing high strength structural steels, and its excellent mechanical properties are more suitable for the use of building structures. In order to study the monotonic mechanical properties of this new steel grade and to obtain the actual mechanical properties of finished plates with different plate thicknesses, monotonic tensile tests were carried out on base material specimens and butt weld joint specimens with different plate thicknesses to obtain the key indicators of the mechanical properties. The effect of the rolling process on the mechanical properties at different plate thicknesses is also analysed, and the differences in the mechanical properties of the butt weld joint with the base material are investigated to assess the reliability of this new high performance steel weld joint.

II. Experimental Program

A. Material Properties

The new high-performance steel is a 690 MPa high-performance seismic and weather-resistant structural building steel (TMCP temperature-controlled tie steel)

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produced by HSC Group, with the grade Q690GJNHE. The diffusion hydrogen content HD=2mL/100g <5mL/100g) [7], the grade HS80GJ. Their main chemical composition content is shown in Table I.

TABLE I. CHEMICAL COMPOSITION OF BASE METAL AND WELDING WIRE (%)

Materials	C	Si	Mn	P	S	Cr	Ni	Cu	Mo
Q690GJ NHE	0.07	0.29	1.41	0.012	0.00 31	0.43	0.72	0.34	0.41
HS80GJ	0.10	0.45	1.80	0.009	0.0 020	-	1.80	0.71	-

B. Trial Overview

A total of 42 standard tensile specimens were designed for this test, of which 21 specimens were taken from the base material and 21 specimens were taken from the butt weld steel plate. For the plate thickness of 16mm and 20mm, respectively, along the rolling direction of each piece of steel plate to take 3 base material specimens and butt weld specimens, a total of 12; for the 45mm thick steel plate, respectively, along the upper surface of the plate to the lower surface of the 5 thicknesses of stratified sampling, single layer specimen thickness of 9mm, each thickness grouping of 3 specimens, a total of 30 specimens. Except for the 45mm thick plate, which was sampled in layers, the rest of the specimens were sampled in full thickness, and all the specimens were sampled by EDM wire cutting, and the sampling locations met the relevant requirements of GB/T 2975 [8].

In order to ensure the uniformity of the test results and to facilitate the later analysis and comparison of the mechanical properties of specimens with different plate thicknesses, the geometry of all tensile specimens conformed to the relevant requirements of GB/T 228.1 [9] and GB/T 2651 [10] for proportional specimens. The standard tensile specimen planar geometry parameters are shown in Fig. 1, where the parallel section design length is 120 mm and width is 15 mm.

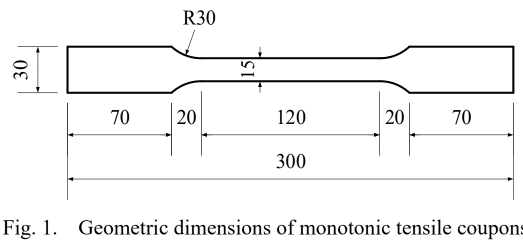


Fig. 1. Geometric dimensions of monotonic tensile coupons.

In order to meet the predicted load of the specimens, specimens with a plate thickness of 16 mm (and 45 mm thick plate layered specimens) were tested in tension using an MTS universal testing machine with a maximum load of 300kN. A 50 mm spaced tensile extensometer was used to record the longitudinal strain in the parallel section during the test. For the full thickness specimens with a thickness of 20 mm, due to the large tensile load and the small stiffness of the beam of the 300 kN load tester, the test accuracy may be affected. All the above testers and extensometers were professionally calibrated and calibrated, and the test results are comparable.

The test loading system is determined by reference to the relevant provisions of GB/T 228.1–2010 [9], the specimen is controlled by stress in the elastic phase, the stress loading rate range is 6–60MPa/s, when the material deformation beyond the elastic phase is controlled by strain, the strain loading rate is 0.002/s, after the specimen necking remove the extensometer and use the test machine beam displacement rate control, until the specimen Pull off.

III. TEST RESULTS AND DISCUSSION

A. Failure Modes

Each base material specimen tensile damage after a large plastic deformation, parallel segment neck shrinkage is obvious, the majority of specimens are in the middle of the parallel segment damage, a small number of specimens in the parallel segment near the transition position damage. Damage to the butt weld specimen as shown in Fig. 2, the specimen in the red shaded mark part of the welded specimen heat affected zone range. It can be seen that most of the butt weld specimens in the weld near the heat-affected zone damage, which can be seen in the butt weld specimens are weak areas in the weld heat-affected zone, thus reducing the load-bearing capacity of the welded specimens.

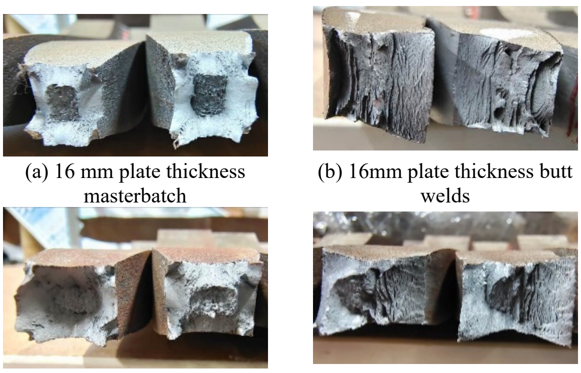
(a) 16 mm plate thickness (b) 20 mm plate thickness

Fig. 2. Photographs of welded joint coupons with different thicknesses after failure.

B. Fracture Analysis

Plastic materials and brittle materials after the destruction of the fracture will show significantly different characteristics, so you can also determine the plasticity and toughness of the base material and welding specimens from the fracture shape, the tensile fracture shape of each specimen is shown in Fig. 3.

All of the base material specimens fracture morphological characteristics are cup-shaped fracture, cup at the bottom of the tough nest is extremely well developed, the edge of the fracture shear lip mark obvious, the overall performance of the more obvious plastic fracture characteristics. Butt weld specimens are damaged after the presentation of the deconstruction fracture fracture, fracture inclination is 45° and can be observed a large number of deconstruction surface, showing obvious macroscopic brittle fracture characteristics, such deconstruction fracture generally occurs in the coarse grain size of the metal area. For 20 mm plate thickness butt weld specimens, as shown in Fig. 3(d), the fracture form is complex, mainly due to the large plate thickness in the welding process using more filler welds, resulting in the root of the weld is less affected by heat input and ultimately still retains a certain degree of plasticity. Welded specimens heat-affected zone embrittlement is mainly due to the heat input of the welding process resulting in the heat-affected zone superheated zone grain coarsening, especially when using a large heat input, coarse grain areas will be due to grain growth or the emergence of Weinstein organization and lead to a sharp decline in plasticity and toughness [11], especially for such fine-grained high-performance steel, grain coarsening on the impact of material degradation will be more significant.



(a) 16 mm plate thickness masterbatch

(b) 16mm plate thickness butt welds

(c) 20 mm plate thickness masterbatch

(d) 20 mm plate thickness butt welds

Fig. 3. Fracture morphology of each coupon in the thickness range of 8 mm–20 mm.

C. Stress-strain Curves

For butt weld specimens, due to the non-homogeneity of the material in the joint area, the deformation in the local area is not coordinated and generally only the tensile ultimate strength and elongation after fracture are analysed in the study, while mechanical parameters such as modulus of elasticity and yield strength are generally not analysed, therefore very little research has been carried out to explore the intrinsic structure model of butt weld joint mechanics. In this paper, with reference to the assumptions related to the mechanics of composite materials, the region of the welded joint with complex composition is simplified to a homogeneous material in the elongation gauge section, and the elongation gauge strain can be regarded as a homogeneous deformation of the equivalent homogeneous material in this section. After the tensile test is completed, the strain parameters are obtained from the displacement of the extensometer during the small deformation phase and from the displacement of the testing machine after the necking of the specimen, resulting in the full stress-strain curve shown in Fig. 5.

IV. Mechanical Properties Analysis

A. Delamination Analysis of 45 mm Thick Plates

In order to analyse in detail the distribution of mechanical properties of the 45 mm thick plate base material and welded specimens at different thickness locations, the static mechanical properties of the specimens at each stratification location are extracted as shown in Table II and their mechanical properties are plotted as shown in Fig. 4 to investigate the key mechanical properties such as yield strength, ultimate strength and elongation after fracture with the thickness location of the changing law. As can be seen from Fig. 4, the mechanical properties of the 45 mm thick base material show great variability with different sampling locations, with the middle layer having the lowest strength and the closer the sampling location is to the rolled surface of the steel, the higher the strength. 13.1%. For the 45 mm thick plate butt weld joints, the mechanical properties of the material are not as regularly distributed along the thickness direction as the base material, but generally show a higher strength for the middle layer and a lower strength for the surface layer, the opposite of the mechanical properties of the base material. For the modulus of elasticity, the modulus of elasticity of the base material hardly varies with the thickness position and is basically stable around 220 GPa, while the modulus of elasticity of the butt weld varies considerably with the layering position and continues to decrease from the top surface to the bottom surface with the thickness layering uniformly, with a difference of 19% between the modulus of elasticity of the first and fifth layers.

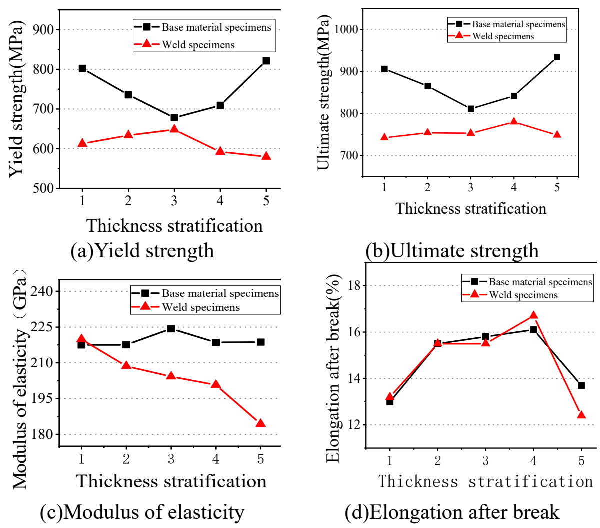
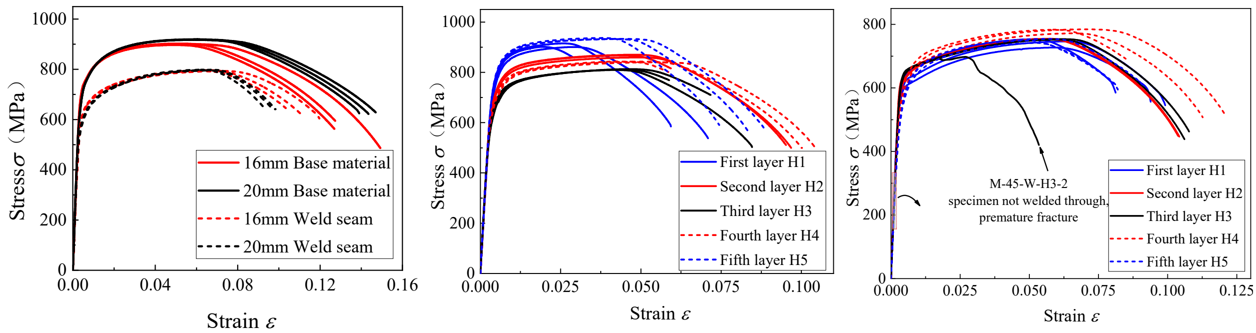


Fig. 4. Variation diagram of mechanical properties of different layers of 45 mm thick plate.

Fig. 4 (d) shows the post-break elongation of the base material and non-butt weld joint specimens of different thickness positions, in general, the base material and weld in the same position at the specimen post-break elongation is approximately the same, that is, the welding process of thick plate does not significantly reduce the ductility of the material. From the point of view of the thickness of the layers, in addition to the surface layer of material ductility sharply reduced, the ductility of the middle layers of specimens remain basically the same, the elongation after fracture are about 16%, in line with the specification for Q690GJ steel ductility index requirements. The ductility distribution of the base material basically satisfies the law of inversion of strength and ductility [12], i.e. the ductility decreases significantly for the stronger surface material.



(a) 8–20 mm plate thickness specimens (b) 45 mm plate thickness masterbatch (c) 45 mm plate thickness butt welds

Fig. 5. Stress-strain curves of the coupons with thickness in the range of 8 mm–45 mm.

TABLE II. MONOTONIC MECHANICAL PROPERTIES OF 45 MM THICK PLATE LAYERED COUPON

Specimen layering	Modulus of elasticity (MPa)	Yield strength (MPa)	Ultimate strength (MPa)	flexural ratio	Yield strain	Extreme strain	Elongation after break	Section shrinkage
Parent material layer 1	217477	802.11	905.87	0.89	0.00569	0.0245	13.0%	55.9%
Parent material layer 2	217559	735.86	865.43	0.85	0.00538	0.0476	15.5%	60.6%
Parent material layer 3	224306	678.31	811.27	0.84	0.00503	0.0436	15.8%	57.8%
Parent material layer 4	218545	708.99	841.92	0.84	0.00524	0.0488	16.1%	61.3%
Parent material layer 5	218672	821.65	933.97	0.88	0.00576	0.0407	13.7%	57.7%
Weld layer 1	219871	612.54	742.44	0.82	0.00479	0.0589	13.2%	51.5%
Weld layer 2	208603	633.64	754.25	0.84	0.00504	0.0571	15.5%	61.5%
Weld layer 3	204207	648.13	752.98	0.86	0.00519	0.0614	15.5%	62.0%
Weld layer 4	200737	592.13	779.99	0.76	0.00495	0.0653	16.7%	60.3%
Weld layer 5	184366	579.77	748.56	0.77	0.00515	0.0526	12.4%	53.5%

The main reason for the different mechanical properties of the above 45 mm thick plate master batch in different layering positions is that, during the cooling process of the controlled temperature and rolling of the steel plate, the uneven cooling phenomenon occurs due to the thicker plate, and the cooling rate gradually decreases from the surface to the inside, resulting in a higher proportion of granular bainite in the middle layer and less slate-like bainite [13]. Granular bainite is a collection of sub-grains with a larger grain size, which has a lower strength than slatted bainite, but a better plasticity and toughness.

B. Analysis of Mechanical Parameters for Different Plate Thicknesses

As can be seen from the stress-strain curves of the specimens of different plate thicknesses in Fig. 5, there is little difference in the static mechanical properties of the steel batch for different plate thicknesses. With reference to the rules of the steel sampling code, the results of the second layer of 45mm thick plate specimens are taken as representative values and Table III shows the static mechanical properties of the 16–45 mm plate thickness base material and butt weld specimens. The modulus of elasticity of the base material and butt weld specimens of different thicknesses is shown in Fig. 6, with the modulus of elasticity of the base material showing a general trend of slowly increasing with increasing plate thickness, with little variation overall, all within the range of 210 GPa to 220 GPa. Comparing the modulus of elasticity of the base material and the butt weld, it can be seen that for all plate thickness specimens, the modulus of elasticity of the butt weld has a certain decline compared to the base material, which is related to the softening of the heat affected zone after welding.

TABLE III. MONOTONIC MECHANICAL PROPERTIES OF COUPONS WITH THICKNESS IN THE RANGE OF 16–45 MM

Specimen type	Specimen plate thickness	Modulus of elasticity (MPa)	Yield strength (MPa)	Ultimate strength (MPa)	flexural ratio	Yield strain	Extreme strain	Elongation after break	Section shrinkage
Base material specimens	16 mm	212762	742.82	899.98	0.83	0.00549	0.0505	18.9%	70.7%
	20 mm	218918	728.50	918.47	0.79	0.00533	0.0590	17.3%	59.4%
	45 mm	217559	735.86	865.43	0.85	0.00538	0.0476	15.5%	60.6%
	Average	216413	735.73	894.63	0.82	0.00540	0.0524	17.2%	63.6%
Butt weld specimens	16 mm	194698	631.94	794.04	0.80	0.00524	0.0676	12.2%	53.8%
	20 mm	210983	597.03	797.02	0.75	0.00483	0.0655	11.8%	48.9%
	45 mm	208603	633.64	754.25	0.84	0.00504	0.0571	15.5%	61.5%
	Average	204761	620.87	781.77	0.79	0.00504	0.0634	13.17%	54.73%

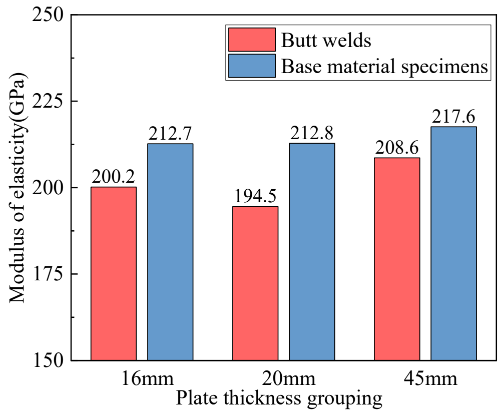


Fig. 6. Variation of young's modulus with plate thickness.

The yield strength and ultimate strength of different thicknesses of base material and butt weld specimens are shown in Fig. 7, where the red reference dashed line is the performance requirements for yield strength and ultimate strength of Q690GJ steel in "Steel plates for structural use in buildings". As can be seen from the graph, the strengths of the 16–45 mm plate thickness specimens are relatively stable and all meet the relevant standards for Q690GJ. Comparison of the base material strength and weld strength in Fig. 7, it can be seen that the strength of the butt weld joint after welding treatment is low, and any plate thickness welded specimens yield strength are maintained in the range of 600–650 MPa, ultimate strength are in the range of 750–800 MPa fluctuations, the change is small. At the same time, the fracture location analysis of the butt weld specimen damage from Fig. 2, all specimens are damaged in the heat-affected zone, which can be launched, the low strength of the butt weld joint is mainly due to the heat-affected zone performance decline caused by.

Different thicknesses of the base material and butt weld specimens of post-break elongation variation law is shown in Fig. 8. As can be seen from the figure, the base material elongation are in the range of 15.5% to 18.9%, which is greater than the specification for Q690GJ steel elongation after break requirements (≥ 14%), while the weld specimens elongation are in the range of 11.8% to 15.5%. The post-break elongation of butt weld specimens are lower than the base material, and with the increase in butt weld specimen plate thickness, the post-break elongation of welded specimens gradually decreases, which is due to the thicker plate welding process, the total heat input is greater, the organization of the heat-affected zone has a greater impact on the properties, resulting in a further reduction in ductility.

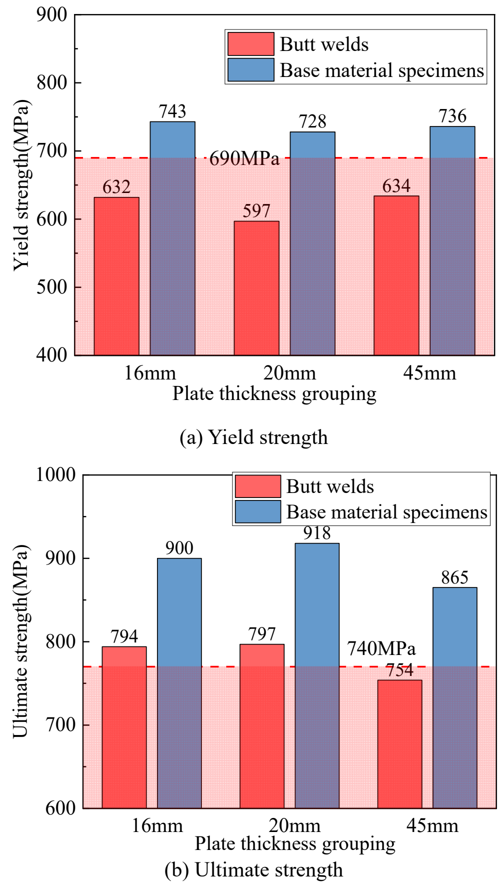


Fig. 7. Variation of strength with plate thickness.

By comparing the strength and ductility differences between the above base material and butt weld specimens, for such fine grain high performance steels, after experiencing the effects of weld heat input, the heat affected zone metal will show an increase in dendrite width and grain size under the weld heat input, despite the macroscopic performance of the weld organization as a full penetration [14, 15].

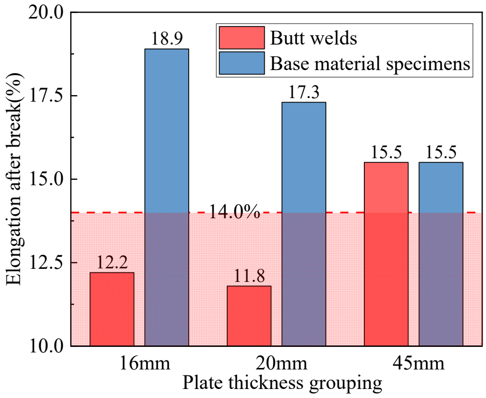


Fig. 8. Variation of elongation after fracture with plate thickness.

In particular, when using a large heat input, coarse grain area will be due to grain growth or the emergence of Weinstein's organization and lead to a sharp decline in plasticity and toughness [11], resulting in welded specimens specimen strength and ductility decline. Therefore, the welding process for such high-performance steel, especially the need to control the welding current and voltage, or to take post-welding heat treatment processes such as normalization, in order to ensure that the welding heat input within a reasonable range, to avoid causing excessive degradation of the base material, heat-affected zone and weld area metallurgical components.

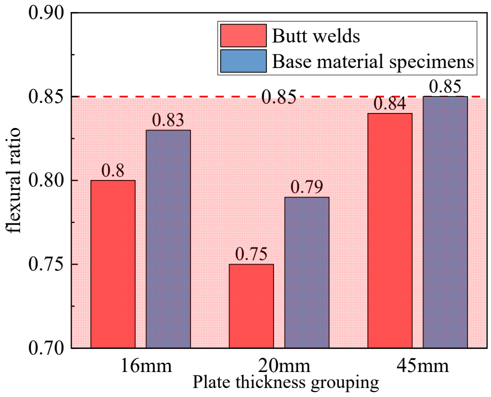


Fig. 9. Variation of yield ratio with plate thickness.

The lower the yield strength ratio, the greater the room for strain strengthening after yielding, and the Code for Structural Steel Plates also limits the yield strength ratio of structural steel to no more than 0.85. Fig. 9 shows the distribution of yield strength ratios for different plate thicknesses and butt weld joints. The results show that the flexural strength ratio of the specimens is lower than 0.85, which is in line with the requirements of the "Structural Steel Plate" specification. Comparing the mechanical properties of the base material and the weld, all the butt weld joints have a lower flexural strength ratio than the base material, and it can be concluded that the butt weld joints have a better strength safety reserve, although the strength is worse than the base material.

V. Conclusion

In this paper, monotonic tensile tests on new high performance steel base materials with different plate thicknesses and their butt weld specimens were carried out, and the assumption of equivalent homogeneous material was introduced, based on which the mechanical properties of the weld were analysed.

(1) The mechanical properties of this new high-performance steel are excellent, with yield strength higher than 690 MPa and elongation after break higher than 15%, while the material yield-to-tensile ratio is less than 0.85, meeting the seismic design requirements of the building material.
(2) The static mechanical properties of the 45mm thick plate base material have an obvious change pattern along the thickness direction, i.e. the strength gradually increases and the ductility gradually decreases from the middle layer to the surface layer.
(3) Compared with the base material, the strength and ductility of the butt weld specimens are low, but the yield strength ratio is generally lower than that of the base material, with the yield strength remaining in the range of 600–650 MPa and the ultimate strength in the range of 750–800 MPa.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Shuai Su wrote the original draft of the paper; Shidong Nie provided conceptualization and methodology; Zhenye Chen reviewed and edited the manuscript; Cheng Ma and Jin Pan provided materials relevant data; all authors had approved the final version.

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