HSS

ARTICLE

CONNECTION DESIGN WITH HIGH-STRENGTH HSS

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Around the world, there is a movement toward "high-performance" or high-strength materials in structural engineering. In the steel construction sector, this has been more evident with plate and wide-flange sections, but hollow section manufacturers are now in the process of raising the strength levels of their products. The use of high-strength steel has the potential to reduce material costs and the self-weight of structures. As opposed to box sections fabricated from plates, higher-strength hollow structural sections (HSS) have been routinely manufactured in Europe for some time by hot-finishing and cold-forming processes (CEN, 2006a;b), with specified nominal yield strengths up to 67 ksi (S460). Now, HSS draft production standards in Europe cater for specified nominal yield strengths of up to 102 ksi (S700) for hot-finished steel hollow sections and up to 139 ksi (S960) for cold-formed steel hollow sections (CEN, 2016a;b), although 100 ksi (S690) yield represents the practical limit for availability. This development has generated considerable research into the member behavior, cross-section classification and material properties of such high-strength sections (Ma et al., 2017). Experimental, numerical and reliability studies by Wang and Gardner (2017) on European hot-finished hollow sections up to S690 (100 ksi yield) have verified the applicability of the AISC 360 (AISC, 2016) column curve to high-strength HSS. A feature of high-strength HSS that is well known is the reduced ductility of the steel relative to lower-strength (50 ksi yield) HSS. For very high-strength steel, the nominal yield-to-tensile strength ratio approaches unity, and the minimum elongation at fracture can be less than 10%.

Domestically, higher-strength cold-formed HSS are now available, produced to ASTM A1110 (ASTM, 2018a) and ASTM A1112 (ASTM, 2018b). A1110 offers two grades (A and B) of ERW HSS in rounds and shapes, with both grades having a Charpy V-notch (CVN) impact toughness rating. Grade A has a minimum yield stress of 52 ksi with a minimum CVN rating of 25 ft-lbs at -20° F; grade B has a minimum yield stress of 57 ksi with a minimum CVN rating of 25 ft-lbs at -40° F. The nominal yield-to-tensile strength (F_y/F_u) ratios of grades A and B are 0.80 and 0.81 respectively. Requests for alternate CVN test temperatures can also be made to the manufacturer. Geometric tolerances are similar to A500 (ASTM, 2018c) such that a design thickness of 0.93t would be assigned and A500 section properties can be used. The higher yield strength offered by the A1110 product, for example relative to A1085 (ASTM, 2015), is clearly marginal and at present production of A1110 in the United States is limited to one manufacturer.

A1112 (ASTM, 2018b) is the newest HSS production standard, providing five grades of high-strength HSS: Class 70, Class 80, Class 90, Class 100 and Class 110, where the class corresponds to the minimum yield stress in ksi. The product is cold-formed using ERW and is again limited in the United States to just one manufacturer. The nominal F_y/F_u ratios are high, as is typical for high-strength steels, ranging from 0.875 to 0.93. There is no CVN toughness rating and the cautionary "Note 1," regarding applicability to dynamic loading given in A500, is reproduced in A1112. A wall thickness tolerance of -5% (as per A1085), but without the tight mass tolerance of A1085, means that a design wall thickness of 0.93t would be assignable and the section properties of A500 can be used for structural design.
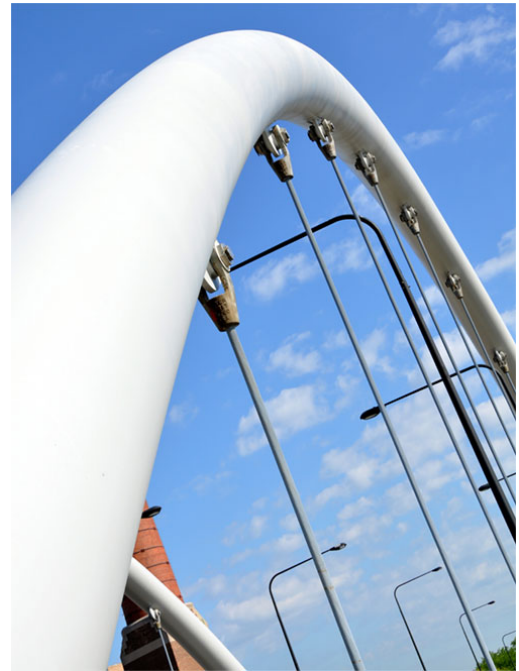
ACCEPTANCE BY DESIGN CODES, SPECIFICATIONS AND GUIDES

ASTM A1110 and ASTM A1112, both published in 2018, clearly do not appear as approved materials in the current AISC Specification (AISC, 2016). A barrier to their use in building construction will be the limits of applicability placed on connection design rules in Chapter K of the Specification where, in Tables K2.1A, K3.1A, K3.2A, K4.1A and K4.2A, there is a requirement for all HSS members to have $F_y \leq 52$ ksi and (F_y/F_u) ≤ 0.8. These material limitations are also included in AISC Design Guide 24 (Packer et al., 2010) and stem from the origin of some of the connection design formulas in Chapter K from the 1980s (IIW, 1989).

More modern international design recommendations for HSS connections (Wardenier et al., 2008; Packer et al., 2009; ISO, 2013) still placed restrictions on material mechanical properties but expanded the HSS strength range to $F_y \leq 67$ ksi (460 MPa). Moreover, if $F_y > 0.8F_u$, the "design yield stress" used for computations was also capped at $0.8F_u$. For steels with a design yield stress greater than 52ksi (355 MPa), the connection resistances given in these guides also had to be multiplied by 0.9 to accommodate connection behavior (discussed below).

The next edition of Eurocode 3 for steel structures will cover the use of steels up to S700 (700 MPa), or approximately 100 ksi yield strength, including hollow sections. This has caused another reexamination of the so-called "material factors" that will be required for HSS connections.

BEHAVIOR OF HIGH-STRENGTH HSS CONNECTIONS

Since high-strength steel has a lower ductility and higher F_y/F_u ratio than mild steel, the propensity for fracture is increased. This means that connection limit states based on fracture failure modes are liable to occur at lower loads than would be expected because the design of welded truss-type connections, for all limit states, is based on the yield stress F_y. This would particularly apply to the limit states of local yielding of the tension branch and punching shear failure of the chord member, but other limit states, which require considerable ductility (such as chord wall plastification in gapped K-connections), would likely be affected. Thus, brittle failures may occur in high-strength HSS connections whereas ductile failures would occur in the corresponding low-strength HSS connections. In order to address this issue, Lalani et al. (1993), Noordhoek et al. (1996) and others have proposed that the design yield stress be limited to $0.8F_u$.

Note that in the AISC Specification (AISC, 2016), when elements are checked for brittle failure modes (such as tensile rupture, shear rupture and block shear in Section J4), AISC 360 assigns a lower resistance factor of $\phi = 0.75$ (for LRFD). Hence, one approach to handling the reduced ductility of high-strength HSS connections might be to add a second limit state check for all failure modes associated with tension branch loading by replacing the yield stress term with the ultimate stress term and employing $\phi = 0.75$.

Another aspect to consider for high-strength steel HSS connections is the influence of an elevated yield stress on connection deformations in ductile failure modes. Some welded HSS connections, particularly those with a low branch-to-chord width (or diameter) ratio, β, have significant chord deformations at their ultimate limit state load, hence even at the service load, the connection deformation may be considered excessive. To avoid a separate check for connection deformation at the service load level, an additional "ultimate deformation limit" was introduced in the 1990s by IIW Subcommission XV-E on Tubular Structures as a means of interpreting experimental or numerical test results. This provided an ultimate load corresponding to an indentation of the chord connecting face equal to 3% of the chord width (or diameter) and became known as the "3% displacement limit," to be used in lieu of the actual ultimate load if 3% chord displacement was reached before the ultimate capacity was reached. As mentioned, this notional 3% displacement limit is used only in research and does not appear in HSS connection design recommendations, but one example of where this ultimate deformation limit governs is with the chord wall plastification limit state expression based on a yield-line mechanism. In that case, the load given by a connection yield-line formula is well below the connection's real ultimate capacity, and it can be seen that φ is even taken as 1.0 in AISC DG24 (Packer et al., 2010), but use of the yield-line mechanism load for the ultimate limit state serves as a deformation-controlling measure at the service load level. For mild steel, Kosteski et al. (2003) has illustrated the approximate correspondence between the HSS connection yield-line formula and the "3% displacement limit."

With high-strength steels, even larger chord deformations (relative to mild steels) may take place in HSS connections for plastification limit states depending on the connection geometry. This phenomenon has led to reduction factors being proposed for connection capacity (calculated based on F_y) to provide a lower "ultimate deformation limit." Mang et al. (1978), Kurobane and Makino (1987), and Puthli et al. (2011) have all proposed HSS connection strength reduction factors of approximately 0.9 for 67 ksi (S460 or 460 MPa) steels and 0.8 for 100 ksi (S690 or 690 MPa) steels. The value of 0.9 was implemented in CIDECT DG1 (Wardenier et al., 2008) and CIDECT DG3 (Packer et al., 2009) for HSS with 52 ksi (355 MPa) < F_y ≤ 67 ksi (460 MPa) as described above.

DESIGN OF WELDED HIGH-STRENGTH HSS CONNECTIONS

To handle the two effects of high-strength steel on the performance of HSS truss connections, namely the reduced ductility and deformation capacity (for brittle failure modes) yet potentially larger chord deformations (for ductile failure modes), a revision has been made to EN 1993-1-8 (CEN, 2019) for the design of HSS welded truss connections of various grades. Clause 9.1.1(4) of this European draft stipulates that the values for connection design resistance should be multiplied by a material factor, C_f, from Table 1 below. In the cases of chord punching shear failure and tensile failure of a branch in addition to multiplying by the material factor C_f given in Table 1, the design yield strength F_y and F_{yb} should not exceed $0.8F_u$ and $0.8F_{ub}$ respectively.

Specified HSS minimum yield stress	Material factor, C_f
F_y ≤ 52 ksi (355 MPa)	1.00
52 ksi (355 MPa) < F_y ≤ 67 ksi (460 MPa)	0.90
67 ksi (460 MPa) < F_y ≤ 80 ksi (550 MPa)	0.86
80 ksi (550 MPa) < F_y ≤ 102 ksi (700 MPa)	0.80

Table 1: Material factors to be applied to HSS welded connection resistance (LRFD and ASD)

Furthermore, this design code allows one to modify the choice of failure modes where the design yield strength is limited to $0.8F_u/F_{ub}$. It is clearly very conservative to apply the material reduction factor, C_f, *and* limit the design yield strength to $0.8F_u/F_{ub}$ at the same time given that these factors are intended to address different connection behaviors. Some researchers (e.g., Becque and Wilkinson, 2017) have questioned this dual penalty, so more study is clearly required into this area to resolve these issues with high-strength HSS. There is, however, consensus that HSS connection design strength (currently calculated based on the material yield stress) cannot be increased in proportion to the yield stress, which partially offsets the benefit of high-strength HSS.

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