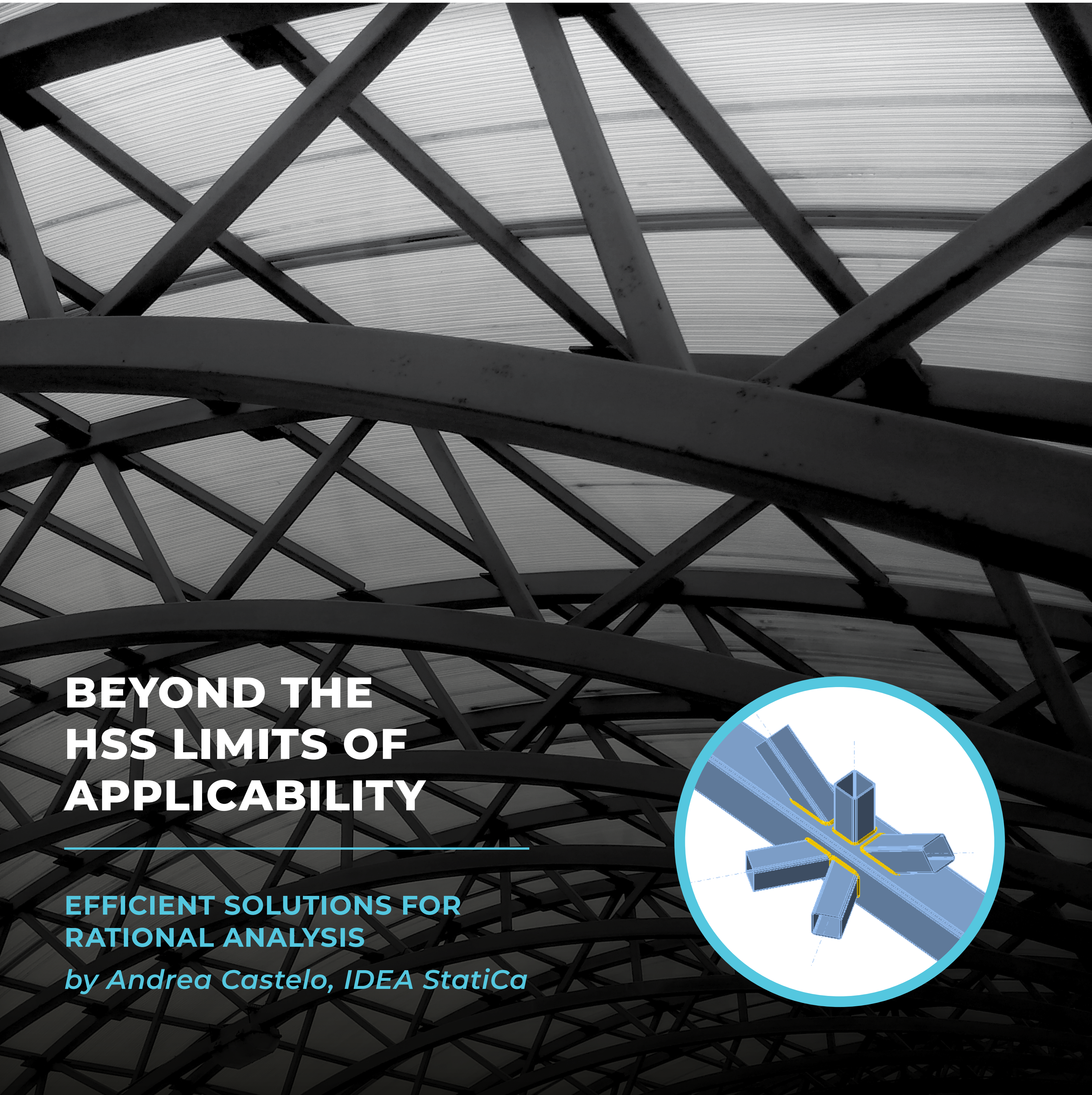


BEYOND THE HSS LIMITS OF APPLICABILITY

EFFICIENT SOLUTIONS FOR RATIONAL ANALYSIS

by Andrea Castelo, IDEA StatiCa

BEYOND THE HSS LIMITS OF APPLICABILITY – EFFICIENT SOLUTIONS FOR RATIONAL ANALYSIS

Written by

Andrea Castelo, IDEA StatiCa

The use of Hollow Structural Sections (HSS) can be the most efficient and cost-effective option for many multistory projects, especially when used as columns and braces. However, some structural engineers believe the use of HSS, particularly regarding connection design, is an obstacle instead of an opportunity. Why?

Well, with structures that have more complex HSS geometries, engineers come across limitations as simple as:

- An HSS member node cannot have more than “X” inches of eccentricity from the working point.
- A truss member cannot have more than “X” degrees with respect to the branch.

WHAT ARE THESE LIMITS?

Known as the limits of applicability, the limits above are just a couple examples of the many that are found in Chapter K of the AISC-360 Specification for Structural Steel Buildings. This chapter contains formulas for the additional limit states (apart from those stated in Chapter J for steel connection design) that relate specifically to the connection design of HSS elements. This chapter has its advantages and disadvantages. If the geometry of the connection of interest is in the tables and does not go outside the applicability limits, the connection can be handled with a pencil and calculator in less than 1 hour.

But, as explained at the beginning of this article, structural projects continue to increase in complexity, and thus connection designs are getting more complex with more connections being outside the limits of applicability regardless of section type.

The design tables in Chapter K are divided by type of joint configuration, cross section type: rectangular or round, and type of force.

Each design table contains applicability limits that can be summarized as:

- HSS wall slenderness
- Width ratio
- Material strength
- Ductility
- Connection eccentricity
- Gaps
- Wall thickness
- HSS sizes
- Aspect ratio

TABLE K3.2A
Limits of Applicability of Table K3.2

Connection eccentricity:	$-0.55 \le e/H \le 0.25$ for K-connections
Chord wall slenderness:	B/t and $H/t \le 35$ for gapped K-connections and T-, Y-, and cross-connections
	$B/t \le 30$ for overlapped K-connections
	$H/t \le 35$ for overlapped K-connections
Branch wall slenderness:	B_b/t_b and $H_b/t_b \le 35$ for tension branch
	$\le 1.25\sqrt{\dfrac{E}{F_{yb}}}$ for compression branch of gapped K-, T-, Y-, and cross-connections
	≤ 35 for compression branch of gapped K-, T-, Y-, and cross-connections
	$\le 1.1\sqrt{\dfrac{E}{F_{yb}}}$ for compression branch of overlapped K-connections
Width ratio:	B_b/B and $H_b/B \ge 0.25$ for T-, Y-, cross-, and overlapped K-connections
Aspect ratio:	$0.5 \le H_b/B_b \le 2.0$ and $0.5 \le H/B \le 2.0$
Overlap:	$25\% \le O_v \le 100\%$ for overlapped K-connections
Branch width ratio:	$B_{bi}/B_{bj} \ge 0.75$ for overlapped K-connections, where subscript *i* refers to the overlapping branch and subscript *j* refers to the overlapped branch
Branch thickness ratio:	$t_{bi}/t_{bj} \le 1.0$ for overlapped K-connections, where subscript *i* refers to the overlapping branch and subscript *j* refers to the overlapped branch
Material strength:	F_y and $F_{yb} \le 52$ ksi (360 MPa)
Ductility:	F_y/F_u and $F_{yb}/F_{ub} \le 0.8$ Note: ASTM A500/A500M Grade C is acceptable.
Additional Limits for Gapped K-Connections	
Width ratio:	B_b/B and $H_b/B \ge 0.1 + \dfrac{\gamma}{50}$
	$\beta_{eff} \ge 0.35$
Gap ratio:	$\xi = g/B \ge 0.5(1-\beta_{eff})$
Gap:	$g \ge t_{b\ compression\ branch} + t_{b\ tension\ branch}$
Branch size:	smaller $B_b \ge 0.63$(larger B_b), if both branches are square

More on the HSS Limits of Applicability as well as several useful summary tables, can be found in this article: https://steeltubeinstitute.org/resources/hss-limits-of-applicability/.

If the configuration of the joint being designed is outside the limits, AISC does not prohibit its design, but mentions that they must be designed by a rational analysis.

BUT WHAT IS A RATIONAL APPROACH?

The Chapter K Commentary explains that the specification doesn't provide guidance on how to design HSS connections which fall outside the limits of applicability, but fortunately, it does provide some insight into the failure modes that should be considered.

Design Guide 24: Hollow Structural Section Connections, in its more recent edition, goes a bit further and provides research and guidance from other international resources. You can read a review of the design guide in the following article: https://steeltubeinstitute.org/resources/aisc-design-guide-no-24-2nd-edition/.

There is no magic formula in the design guide for HSS connections outside of the limits of applicability; however, the design guide helps clarify the physical meaning and behavior of the limit states, which can be extrapolated via "engineering judgment" to other connection cases outside the Chapter K tables and Design Guide 24. Again, this is helpful, but exploring these more complex scenarios can be time-consuming, especially when only employing basic hand calculations, or other simple calculation tools like Excel, Mathcad, etc.

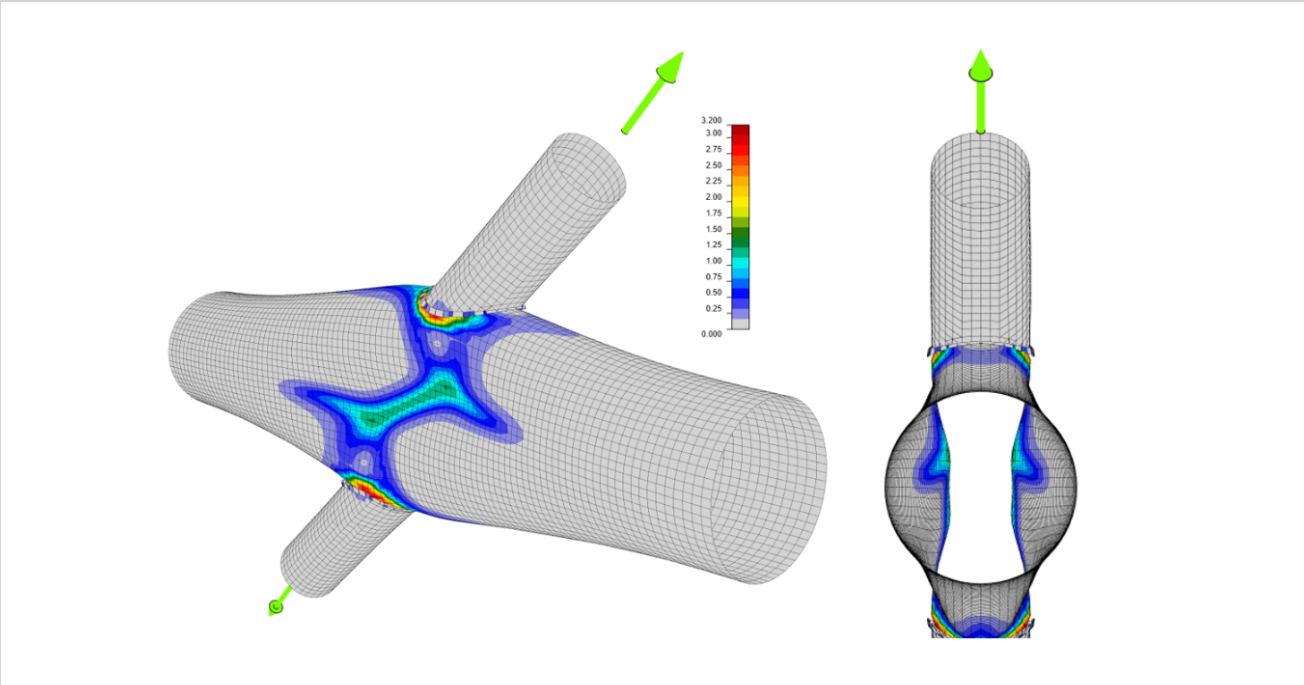
As noted in Chapter 2.13 of AISC Design Guide 24, available testing—both experimental and numerical—has been limited in scope. Because of this, the AISC Specification does not provide design formulas for all HSS joint configurations. In cases outside of the scope, alternative methods such as rational analysis may be used.

WHAT IF ENGINEERS HAD THE CAPABILITY TO HANDLE THESE NUMERICAL EXPERIMENTS USING COMMON COMMERCIAL TOOLS?

Chapter 2.13 talks about the use and acceptance of finite element analysis for HSS connections in the specification. Also, it explains what the recommendations and conditions are for using finite element modelling. In general, the user needs to ensure:

- Inelastic analysis
- Nonlinear analysis
- Adequate nodes and elements
- Correct FE element types
- FE Model, mesh and material verified against benchmark cases
- FE Model validation against laboratory experiments

The majority of Design Guide 24 references finite element studies to their recommendations and formulas. HSS members, due to their geometry, often have flexible connection components, which cannot be accurately captured with simple elastic design formulas. The nonlinear analysis used in FE methods allows the effects of geometry and loading to be handled in a more realistic way.



Advancements in commercial tools allow engineers to design HSS connections without the hassle of being restrained by any limits of applicability, while also being able to perform their analysis quickly, and through an integrated process with an engineer's typical analysis software workflow.

Professor Frantisek Wald, cited in Chapter 2.13 of the Design Guide 24, is one of the founding fathers of the Component-Based Finite Element Method (CBFEM), a method that synergizes the Component Method and FE analysis to allow for the design and code-check of steel joint, anchors and steel members. Professor Wald also worked closely with the structural software company IDEA StatiCa when creating the first FEA connection design solution, commercially released just 10 years ago.

Based on the CB-FEM method developed by Professor Wald, below are recommended elements that an FEA application should have in order to design HSS connections. IDEA StatiCa is one application that includes these elements:

- Material nonlinear analysis: Steel is modelled as an elastic-plastic material and the behavior is based on the von Mises yield criterion. The welds are modelled with a special elastic-plastic material.
- Geometrically nonlinear analysis: When using HSS sections, the analysis considers geometrically nonlinear analysis, that means the deformations are nonlinear.
- No limitation in shell elements and mesh is editable.
- Steel members, plates and welds are converted into shell elements. Bolts are nonlinear spring elements.
- FE model validation and verification: https://www.ideastatica.com/support-center-verifications.

Professor Frantisek Wald et al (Denavit, Nassiri, Mahamid, Vild, Wald and Sezen) published a book called "Steel Connection Design by Inelastic Analysis" which contains the results of research with several universities and validates the CBFEM approach when compared to test results and high-end analysis engines for the requirements of the AISC code (https://www.wiley.com/en-us/Steel+Connection+Design+by+Inelastic+Analysis-p-9781394222155).

EXAMPLE OF AN HSS CONNECTION DESIGN USING INELASTIC ANALYSIS

An example of an HSS connection design will be demonstrated using IDEA StatiCa.

An example is a multiplanar HSS truss connection and is a combination of a gapped KT connection in one plane and a K joint in the other plane.

Chord: HSS 8X8X0.375

Branches: HSS 4x4x0.250

Material: A500 Gr. C

The entire connection design is easily handled in the software. In the video below, the process of modelling, loading, boundary conditions, analysis and results review in IDEA StatiCa is shown.

Multiplanar truss HSS Connection.mp4

Limit states for members and plates are handled by using materially nonlinear analysis (MNA) and geometrically and materially nonlinear analysis (GMNA). The application ensures that all the effects are captured and as a result you get the maximum stresses and strains. The failure limit of the members/plates is related to the maximum strains reported.

To ensure that the strain limit within the software aligns with AISC limit states, IDEA StatiCa worked together with U.S. universities to validate and verify the solution. A catalog of AISC limit states was compiled: https://www.ideastatica.com/support-center/catalog-of-aisc-limit-states-and-design-requirements. The different limit states are explored and compared vs. IDEA StatiCa results. Overall, the differences are between 5% to 10%, with IDEA StatiCa always on the conservative side.

For other components such as bolts, welds and anchors, the application uses the analysis results and plugs them into the AISC formulas to confirm the design.

For a detailed walkthrough on designing and code-checking a tubular 3D frame connection in accordance with AISC standards, refer to the following tutorial: https://www.ideastatica.com/support-center/tubular-3d-frame-aisc.

SUMMARY

Understanding the Chapter K limits of applicability is an important part of accurately designing HSS connections. With the increasing complexity of projects that structural engineers are being asked to take on, it's not uncommon to come across connections that are outside the bounds of the Chapter K limits. Fortunately, AISC allows the engineer to design connections beyond the limits of applicability by using a "rational analysis." By pairing advancements in higher level analysis methodology with tools like IDEA StatiCa, structural engineers now have efficient and effective ways to solve all their HSS connections.

REFERENCES:

1. AISC. 2022. "Specification for Structural Steel Buildings," ANSI/AISC 360–22, American Institute of Steel Construction, Chicago, IL.

2. Packer, J.A. and Olson, K. 2024. "Hollow Structural Section Connections," Steel Design

3. Guide No. 24, 2nd edition, American Institute of Steel Construction, Chicago, IL.