Catalog of AISC Limit States and Design Requirements

Speaker: Mark D. Denavit, Ph.D., P.E.
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About the Speaker

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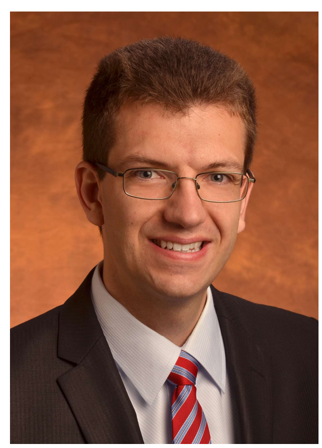

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Outline of the Webinar

- Overview of the catalog
- Discussion on specific entries
  - Weld rupture
  - Shear yielding and rupture
  - Design basis
- Future of the catalog

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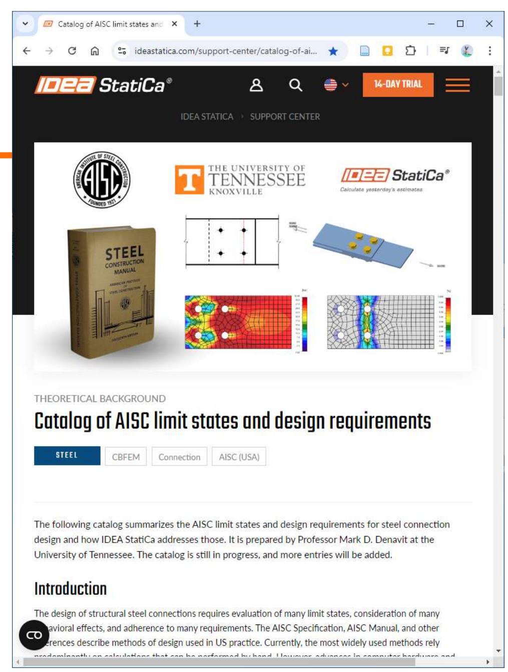
Overview of the Catalog

Available on the IDEA StatiCa website:

https://www.ideastatica.com/support-center/catalog-of-aisc-limit-states-and-design-requirements

Outline:

- Introduction
- Limit States
  - …
- Design Considerations and Requirements
  - …
- References



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Introduction

- Structural steel connection design requires:
  - evaluation of many limit states
  - consideration of many behavioral effects
  - adherence to many requirements
- The use of nonlinear analysis in design can be advantageous for complex or unique connections, where the assumptions of traditional calculations are unproven. **Yet, the same limit states, design considerations, and design requirements apply.**

Definition of Limit State

"Condition in which a structure or component becomes unfit for service and is judged either to be no longer useful for its intended function (serviceability limit state) or to have reached its ultimate load-carrying capacity (strength limit state)."

- 2022 AISC Specification

Limit States

- Weld Rupture
- Weld Base Metal Strength
- Bolt Shear and Tensile Rupture
- Bearing and Tearout at Bolt Holes
- Bearing (Local Compressive Yielding)
- Slip
- Tensile Yielding
- Tensile Rupture
- Compressive Yielding and Buckling
- Shear Yielding and Rupture
- Yielding Under Combined Actions
- Block Shear Rupture
- Flexural Yielding
- Flexural Rupture
- Concrete Crushing
- Flange Local Bending
- Web Local Yielding
- Web Compression Buckling
- Web Panel-Zone Shear Yielding
- Connections to HSS Members

Design Considerations and Requirements

- Design Basis
- Structural Steel Materials
- Prying Action
- Deformation Compatibility in Long Connections
- Deformation Compatibility in Eccentrically Loaded Bolt and Weld Groups
- Bolts in Combination with Welds
- Effect of Hole Size
- Mill Underrun
- Contact and Friction
- Net Area Determination
- Fillet Weld Size Requirements
- Design Wall Thickness for HSS

Outline of a Typical Entry

- A description of the limit state, consideration, or requirement
  - focusing on physical characteristics
- How it is handled in traditional calculations
- How it is handled in IDEA StatiCa
- Example of differences

References

- 2022 AISC Specification
- 16th Edition AISC Manual
- RCSC Guide to Design Criteria for Bolted and Riveted Joints
- AISC Engineering Journal articles
- Modern Steel Construction articles
- and more

Discussion on Specific Entries

- Weld rupture
  - Fillet weld size requirements
  - Deformation compatibility in long connections
- Shear yielding and rupture
- Design basis

Weld Rupture Entry

- The weld rupture catalog entry focuses on fillet welds
- The AISC Specification includes provisions for groove welds, fillet welds, and plug and slot welds.
  - Complete joint penetration (CJP) groove welds are modeled in IDEA StatiCa by directly connecting the components using multi-point constraints. The multi-point constraints introduce no flexibility. Also, the strength of these welds is not checked since the strength of the CJP groove welds is controlled by the base metal.
  - Partial joint penetration (PJP) groove welds are new to IDEA StatiCa and not yet covered in the catalog entry.
  - Plug and slot welds are not available in IDEA StatiCa.

Traditional Calculations

- AISC Spec. Eq. B3-1 for LRFD

$$R_u \leq \phi R_n$$

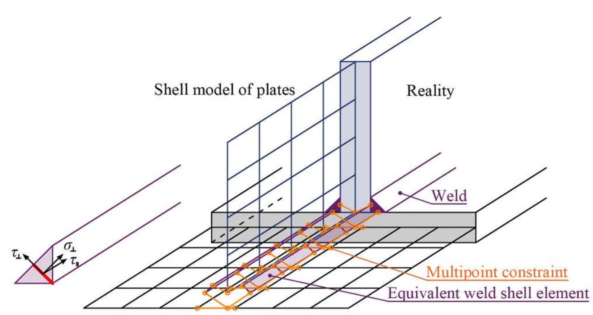
- The available strength of welds is defined in AISC Spec. Section J2.4.

$$R_n = F_{nw} A_{we} k_{ds}$$

- $F_{nw} = 0.6F_{EXX}$, the nominal stress of the weld metal (AISC Spec. Table J2.5)
- A_{we}, the effective area of the weld defined in AISC Spec. Section J2.2a as effective length multiplied by effective throat.
- k_{ds}, a directional strength increase factor

Modelling in IDEA StatiCa

- Fillet welds are modeled in IDEA StatiCa using multi-point constraints and an equivalent weld shell element that approximates the elastoplastic behavior of the weld.
- The forces in these shell elements are extracted and used as required strengths, R_u, for comparison to available strengths computed according to the AISC Specification, ϕR_n.



Evaluation in IDEA StatiCa

- Each weld is broken up into short segments.
- For each weld segment,
  - R_u and the angle of loading are taken from the CBFEM model
  - $F_{nw} = 0.6F_{EXX}$
  - A_{we} is taken as the throat thickness times the length of the weld segment
  - k_{ds} computed using AISC Spec. Eq. J2-5
  - Utilization is $R_u/\phi R_n$
- Detailed calculations for weld segment with maximum utilization reported for each weld.

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Directional Strength Increase

- The directional strength increase factor is defined in AISC Spec. Section J2.4.
- When strain compatibility of the various weld elements is considered (as is the case in IDEA StatiCa because the stiffness of the welds and connecting elements are explicitly modeled)

$$k_{ds} = (1.0 + 0.50\sin^{1.5}\theta)$$

- A special case applies for fillet welds to the ends of rectangular HSS loaded in tension where k_{ds} = 1.0. In IDEA StatiCa, the directional strength increase factor is not used for fillet welds to the ends of rectangular HSS, regardless of loading.

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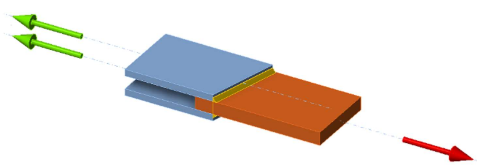
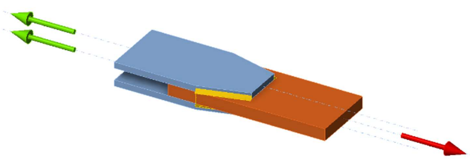
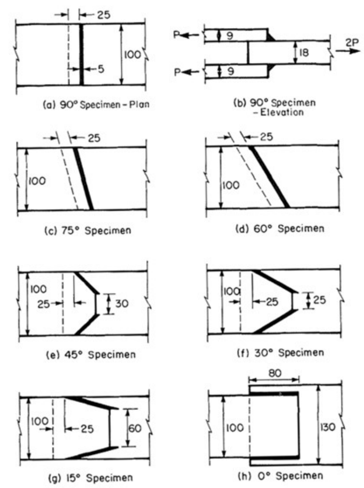
Directional Strength Increase

- To illustrate the effect of the directional strength increase, consider the welded specimens tested experimentally by Miazga and Kennedy (1989).
- The specimens had loading angles of 0, 15, 30, 45, 60, 75, and 90 degrees as shown in the figure below where the units are millimeters.

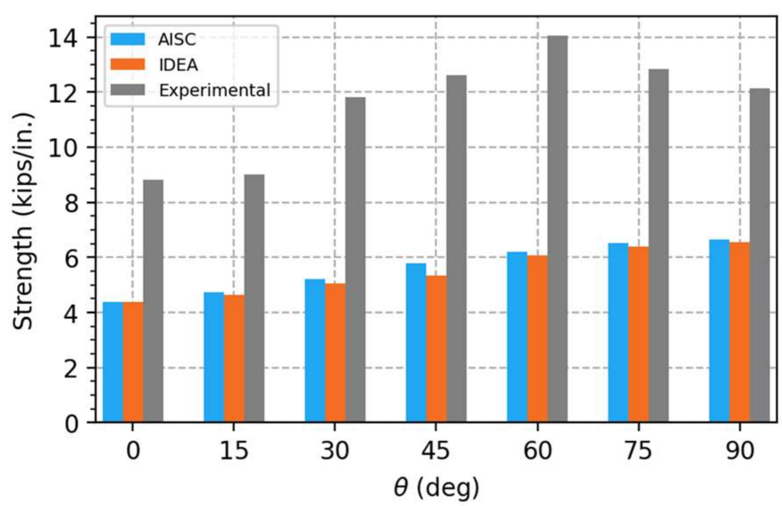






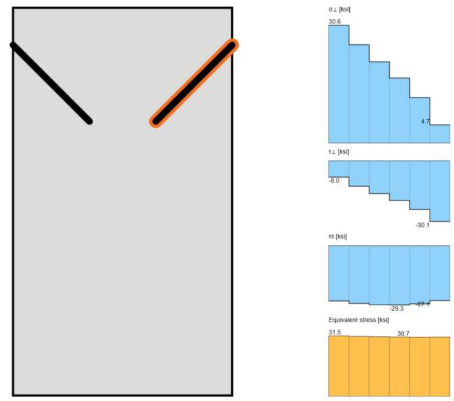
From Miazga and Kennedy (1989)

Strength Results



Angle Results

Geometric θ (deg)	IDEA θ (deg)
0	14.7
15	21.1
30	34.0
45	49.1
60	58.8
75	72.6
90	89.9



Stress components for 45 deg specimen

Fillet Weld Size Requirements

- The effective area of a fillet weld is defined in AISC Spec. Section J2.2a as effective length multiplied by effective throat.
  - but there are some details…

Fillet Weld Size Requirements

Fillet Weld Size Requirements

AISC Specification (2022) Section J2.2b includes limitations for fillet welds.

Items (a)-(c) of Section J2.2b specify geometric limitations on the size and minimum length of fillet welds. These limitations are checked during the calculation if the "Detailing" option is checked in the "Code setup". The specific limitations checked are described in this article. A weld will not pass the code check due to a detailing error if any limitations are not satisfied. Dimensions near or at the limit may not be evaluated as expected due to numerical precision or rounding.

Item (d) of Section J2.2b specifies the effective length of fillet welds including reductions for long end-loaded fillet welds. IDEA StatiCa does not compute the effective length for fillet welds and thus does not use these provision's direction, but the effect of non-uniform stress distribution on the strength of end-loaded fillet welds is captured through explicit modeling of the stiffness of the weld and connected material. See this article for a detailed investigation of this provision.

Items (e)-(i) of Section J2.2b specify limitations that are not checked by IDEA StatiCa and, if applicable, must be evaluated by the engineer separately.

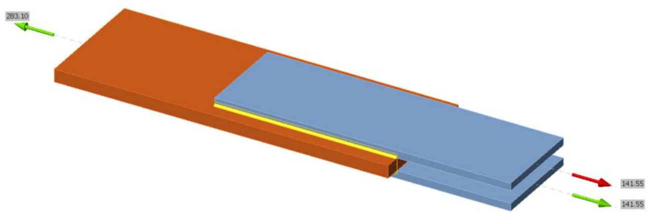
Deformation Compatibility in Long Connections

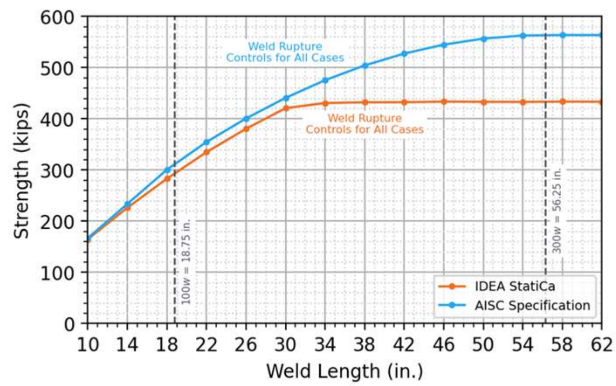
Deformation Compatibility in Long Connections

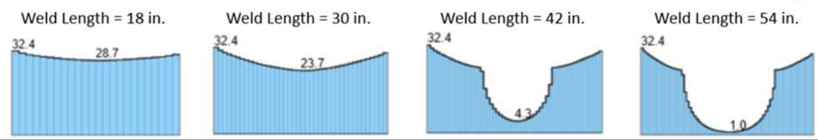
In long end-loaded connections, the difference in elongation between the connected elements is greatest at the ends of the connection. As a result, the stress in bolts and welds in long end-loaded connections is not uniform. Since it is common in traditional calculations to assume uniform stress, the AISC Specification includes reductions to the length of long end-loaded welds and to the nominal shear stress of bolts. AISC Specification Section J2.2b defines the effective length of end-loaded fillet welds including reductions when the length of the weld exceeds 100 times the weld size. The values of nominal shear stress in AISC Specification Table J3.2 include a 10% reduction to account for length effects and an additional reduction is required for end-loaded connections with a fastener pattern length greater than 38 in.

IDEA StatiCa does not implement these reductions directly. Rather, the underlying behavior that motivates these reductions is modeled explicitly. IDEA StatiCa models the stiffness of bolts, welds, and connecting elements, thus the non-uniform distribution of stress in bolts and welds arises naturally. With the strength of bolts and weld segments assessed individually, the resulting connection strength is comparable to that from traditional calculations. A detailed comparison between IDEA StatiCa and determined from traditional calculations for long end-loaded connections is presented in this article.

Long Welded Connections







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Shear Yielding and Rupture

Shear Yielding and Rupture

The available strength of affected elements of members and connecting elements in shear is defined in AISC Specification Section J4.2. This section describes two limit states: shear yielding and shear rupture. For both limit states, IDEA StatiCa does not compute the available strength per the AISC Specification, but rather relies on the 5% plastic strain limit to evaluate if the connection is sufficiently strong.

In tension, the stress-strain relationship used in IDEA StatiCa is linear up to yield, with a stiffness equal to the modulus of elasticity, then linear thereafter, with a stiffness equal to one-thousandth of the modulus of elasticity. Yield in tension occurs at the specified minimum yield stress of the steel, F_y, times 0.9 for LRFD or divided by 1.67 for ASD. IDEA StatiCa uses the von Mises yield criterion to determine when yielding begins under multi-axial states of stress. According to the von Mises yield criterion, material subject to pure shear will yield when the shear stress equals the yield stress divided by the square root of 3. The inverse of the square root of 3 is approximately equal to 0.577 which is approximately equal to the 0.6 factor applied to the shear strength equations in the AISC Specification. This difference, or similar differences when the element is not strictly in pure shear, can lead to differences between IDEA StatiCa and traditional calculations. The small amount of strain hardening can also lead

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Traditional Calculations

- AISC Spec. Eq. B3-1 for LRFD

$$R_u \leq \phi R_n$$

- The available strength for elements in shear is defined in AISC Spec. Section J4.2.

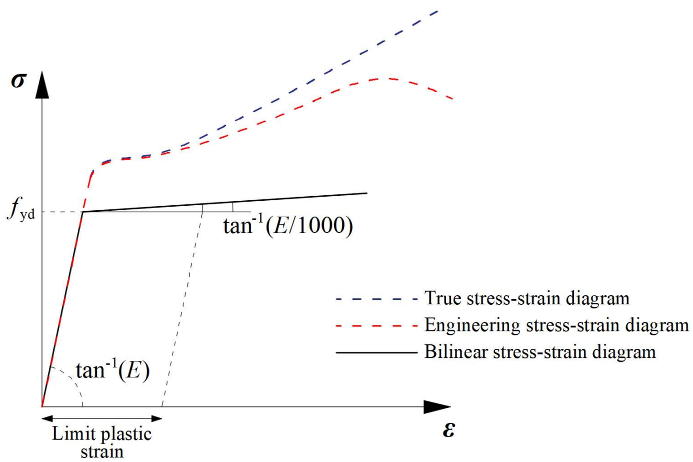
Shear Yield	$R_n = 0.6F_yA_{gv}$	$\phi = 1.00$
Shear Rupture	$R_n = 0.6F_uA_{nv}$	$\phi = 0.75$

- A_{gv} = gross area subjected to shear
- A_{nv} = net area subjected to shear

Evaluation in IDEA StatiCa

- IDEA StatiCa relies on the 5% plastic strain limit to evaluate if the connection is sufficiently strong for the limit states of shear yielding and shear rupture.
- For shear yielding, there are some differences:
  - Resistance factors
  - Small hardening stiffness in IDEA StatiCa
  - 0.6 vs von Mises yield criterion

Resistance Factors



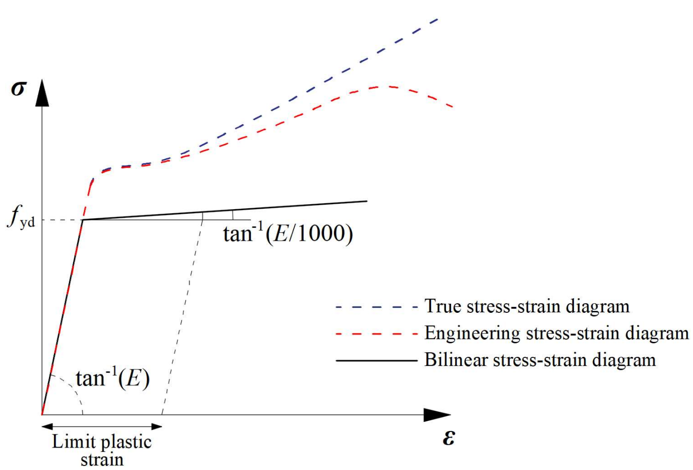
For LRFD:

$$f_{yd} = 0.90F_y$$

Based on typical resistance factor for yielding (ϕ = 0.90)

However, the resistance factor for shear yielding is ϕ = 1.00

Small Hardening Stress



Stress at plastic strain limit:

$$0.90F_y + 0.05\left(\frac{E}{1000}\right)$$

For $E = 29{,}000$ ksi

$$0.90F_y + 1.45\ ksi$$

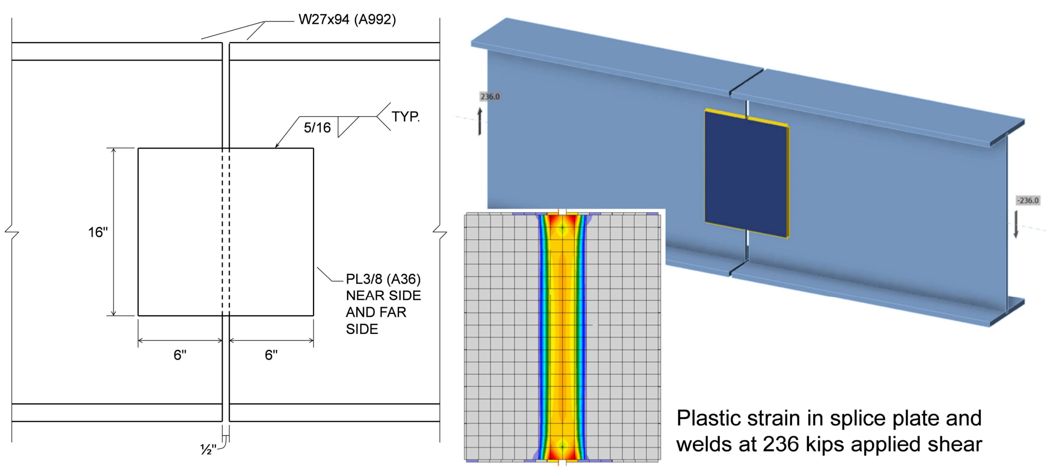
0.6 vs von Mises yield criterion

- IDEA StatiCa uses the von Mises yield criterion to determine when yielding begins under multi-axial states of stress.
- According to the von Mises yield criterion, material subject to pure shear will yield when the shear stress equals $F_y/\sqrt{3}$

$$1/\sqrt{3} \approx 0.577 \approx 0.6$$

- This difference, or similar differences when the element is not strictly in pure shear, can lead to differences between IDEA StatiCa and traditional calculations.

Result of Differences (Shear Yielding)



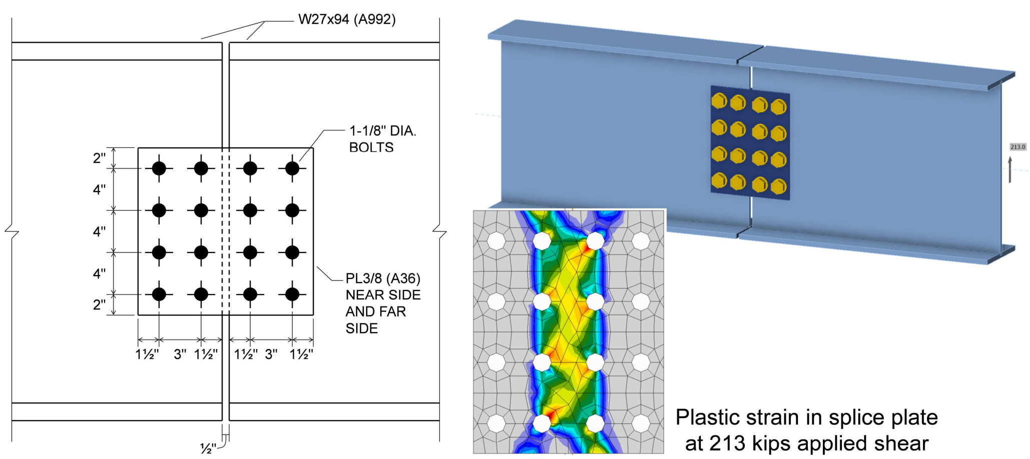
Plastic strain in splice plate and welds at 236 kips applied shear

WELDED SPLICE

Additional Differences for Shear Rupture

- Yield point
  - F_y not F_u
  - $\phi = 0.90$ not $\phi = 0.75$
  - The result of these differences depends on F_u/F_y
- For bolted connections:
  - The net area subjected to shear typically passes through the centerlines of the bolts, but the distribution of plastic strains at the limit point in IDEA StatiCa can be different.
  - IDEA StatiCa does not increase the width of a bolt hole by 1/16 in.

Result of Differences (Shear Rupture)



BOLTED SPLICE

Design Basis

- Design for strength according to the AISC Specification is performed with either the provisions for
  - Load and Resistance Factor Design (LRFD)
  - Allowable Strength Design (ASD)
- While these two approaches have different required strengths and different available strengths, the nominal strengths are the same and final designs should be similar if not the same.

Design Basis

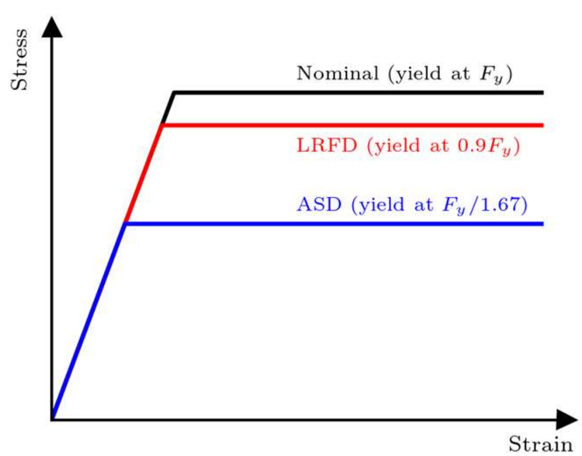
	Strength Criteria	Required Strength	Available Strength	Nominal Strength
LRFD	$R_u \leq \phi R_n$	R_u computed using LRFD load combinations (e.g., $1.2D + 1.6L + 0.5L_r$)	ϕR_n also referred to as the design strength (ϕ is a resistance factor)	R_n
ASD	$R_a \leq R_n/\Omega$	R_a computed using ASD load combinations (e.g., $D + L$)	R_n/Ω also referred to as the allowable strength (Ω is a safety factor)	R_n

Design Basis

- Required strengths are greater for LRFD than for ASD due to the greater load factors in the LRFD load combinations.
- Differences in required strengths can also arise when required strengths are computed using nonlinear analysis and the level of nonlinearity depends on the level of loading.
- To compensate for this in design for stability the AISC Specification requires that all load-dependent effects be calculated at a level of loading corresponding to LRFD load combinations or 1.6 times ASD load combinations.
  - Commonly implemented with the force level modification factor, α = 1.0 (LRFD); α = 1.6 (ASD)

Design Basis

- IDEA StatiCa uses a different approach.
- The yield stress for shell elements is taken as
  - $0.9F_y$ for LRFD
  - $F_y/1.67$ for ASD
- The constitutive relations for bolts and welds are reduced similarly.
- For most cases, this results in maximum permitted applied loads that are 1.5 times greater for LRFD than they are for ASD, consistent with the provisions of the AISC Specification.



Design Basis

- However, the modulus of elasticity is not reduced in IDEA StatiCa for either LRFD or ASD.
- Therefore, the ratio of stiffness to strength differs between approaches resulting in some consequences in design.
  - For buckling, the limiting elastic buckling load ratio differs between LRFD and ASD.
  - Where the stiffness of a connection impacts its strength, e.g., long welded connections, the ratio of maximum permitted applied load between LRFD and ASD can deviate from 1.5.
- Most of the validation studies comparing IDEA StatiCa to the AISC Specification were performed for LRFD.

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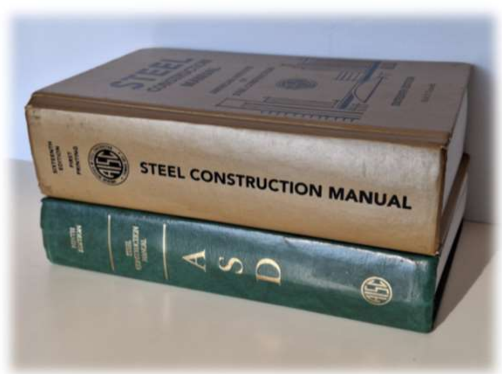
Design Basis

- IDEA StatiCa implements provisions for ASD as defined in the 2022 AISC Specification.
- The provisions in the 2022 AISC Specification for ASD differ from those in historic standards such as the 1989 AISC Specification which is included in the 9th edition AISC Manual (commonly referred to as the “green book”).
- The historic provisions for ASD focused on elastic behavior and had more differences with LRFD.
- The current provisions for ASD are more consistent with LRFD, including common nominal strength calculations.



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Future of the Catalog

- Development of the catalog continues as new entries are written and new versions of IDEA StatiCa are released.
- Other potential catalog entries:
  - Partial joint penetration (PJP) groove welds
  - Shear buckling
  - Lateral-torsional buckling
  - Flexural local buckling
  - Web sidesway buckling

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