

Structural Support Design Guidelines

Christine Ader, Michael McGee, and Robert Reilly

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1.0 Purpose and Scope

This is a structural support design guideline intended for a wide audience; Engineers, Designers and Technical Staff. There is an emphasis placed on support design within accelerators and practical structural issues and assumptions are discussed. The project should provide specifications for required stand (tolerance, weight of device, etc).

2.0 Technical Requirements and Specifications

The project management should provide the technical requirements of the structural support. The information provided should include magnet type, magnet orientation (the buss connections may impact the design), motorized versus non-motorized stand, and alignment tolerances.

Alignment tolerances horizontally and vertically is typically 5 to 10 mils, most often 0.25 mm (10 mils) for accelerators. For stationing (along the Z-axis), the tolerances are typically 100 to 200 mils. (In station, the tolerance is usually more relaxed, typically 0.25 mm, but it is usually not absolutely necessary). The transfer lines and single pass lines are typically less stringent.

3.0 Stand Design

Three-point stands should be used, unless there is a good reason that it cannot be used, in which a 4-point stand could be used. Three-point stands are preferred since even for at 4-point stand, the weight will be distributed along 3 points, not four. For calculations on a 4-point stand, assume that the load is distributed on only 3 points. Be cautious of over-constraining 4-point stands.

When considering re-using any stand design, determine if old engineering notes exist and/or if a new engineering note should be written and/or if the design is robust and/or functional. Do not assume functionality or strength of old design is adequate without analysis and review.

For ceiling stands, if possible, have extra holes for the Hilti's. In that case, specify the minimum number required or have the engineer consulted. Another option is to have pre-drilled tabs fabricated which can be welded on the stand if there are interference issues. Any stands that get installed in ceiling must meet the Hilti installation procedure requirements in FESHM 7080 Concrete Anchor Devices.

Holes in the stand feet should be far enough away from the upright verticals in order to get the hilti hammer drill in (typically 2 to 3"). There is a 2" radius from the bit to the drill motor.

Slots should be perpendicular to the beam direction (only if the stand adjustability does not account for this error, otherwise it is expensive to machine in slots in all stands).

- For ½” Hilti drop-ins, the holes should be 11/16”.
- For 5/8” Hilti drop-ins, the holes should be 29/32”
- For the ½” Hilti Kwik-bolts, the holes should be 9/16.

These numbers would apply to either holes or slots. All the numbers are 1/16” oversized from the drill per the Hilti Technical Guide.

Vertical adjustment should either have a hard stop or provide that the end of adjustment threads are visible.

For very tall stand, either the legs should be angled, or provide cross bracing, for structural truss triangulation, as done on MiniBooNE B872 and Q874-875.

If a magnet traps another magnet, provide that the first magnet can be removed and the supporting members can be removed easily in order to change the second magnet, as was done on NUMI and ANU extraction.

If a magnet spans a change in floor level, it is generally better to support the magnet on two stands, one on each level, but provide the means to install this magnet, such as sideways moving rollers as was done on Numi extraction.

For small stands, the base plate should be one unit or attached to each other in order to maintain square-ness and parallelism, as long as it does not create a binding situation.

Do not put two large magnets on one stand or tied on one stand. This was done for the B2 magnets for NuMI and were very difficult to align.

Consider how the magnet will be installed before finalizing the design. (mono-rail, Hillman rollers, Elwell, Rico Forklift, etc). Have assembly drawings which include installation steps shown. This will help to mitigate installation interferences.

In terms of support stability, an engineer should consider a tipping or seismic analysis.

Motorized stands should have hard stops in order to prevent motion beyond the intended design and/or limit switches.

Consider whether there is a need for forklift lifting points or pads to be incorporated as a permanent part of the stand. If so, measure the actual forks and do not rely on drawings.

3.1 Material Selection

The type of steel selected may impact magnetic field so the machine physicists need to be consulted regarding these potential issues. Additionally, the environmental conditions need to be understood.

For example, the links of grade 100 alloy steel chain failed while supporting the 23-ton steel modules in the MiniBooNE 25-meter absorber in 2007. The report notes a threshold hardness of 35 Rc (UTS of about 160 ksi) for the potential of hydrogen cracking. Note that this was in a severe high humidity, nitric

acid environment that was also stagnant. In the severe target hall environments they try to use 316SS bolts where the ultimate strength is not required and they use grade 5 titanium where they need a high strength fastener. For the NuMI target hall, it is suggested to stay away from grade 8 bolts for a new installation.

3.2 Stand Lubrication

Sliding or threaded surfaces should never be painted. The coefficient of friction of paint is high so the stand may not slide well. Additionally, the paint could also gall or gum up. This is true also for threaded and acme threaded rod surfaces.

For sliding surface or if a sliding surface is painted, use Multifil 426 bearing tape (which replaced Glacier Plate, Garlock DU Flat Group 2 material, which contained lead) which can be cut and put between two metal surfaces to reduce the coefficient of friction. Please note that water will bead-up on the bearing side, while the bonding side will appear wet. So it is critical to note the orientation the tape is placed. Another option is to use powder coat for sliding surfaces. This will have to be determined during the design phase. If stands are made from Aluminum, the sliding surfaces can be dicronited to reduce the coefficient of friction and create a much better sliding surface.

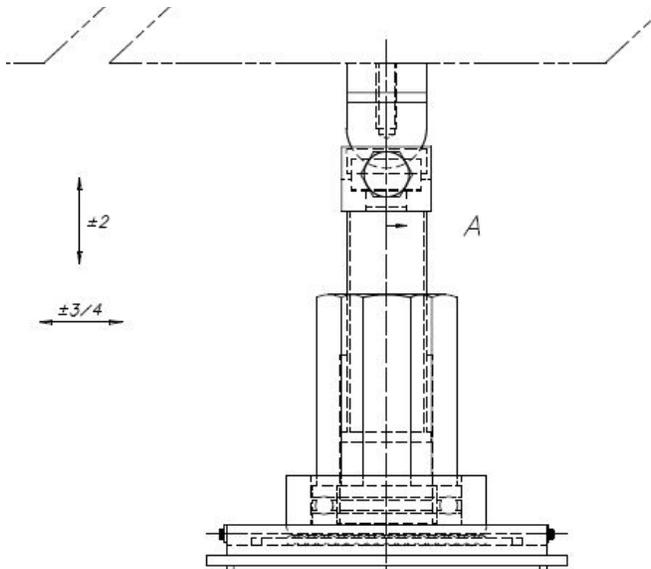
Threaded parts could be greased, but grease attracts dirt which can cause long-term problems. Threaded parts can be coated (zinc-chromate is commonly specified) to eliminate the need for grease.

3.3 Blind Threaded or ACME Holes for Vertical Support

Blind holes, either threaded or ACME, used for vertical support is a serious safety concern. If the vertical support rod is turned to install or align the magnet (to raise or lower), the rigging or Alignment crew has no way to know when the rod is going to screw out of the nut and then the magnet could fall. There has been a couple of incidents in the Main Ring and Switchyard where this has happened.

One should be able to see the end of the threaded rod or it has to be captured. If possible, drilling sight holes should be considered for existing blind holes if possible.

With the big ACME stands for Main Injector, the bottom of the nut was counter-bored with a wider diameter hole and then screwed a disc to the bottom of the threaded stud, which acted as a “stop” preventing the stud from ever coming out of the nut. Here is a drawing of that assembly:



If using re-using stands, then you must consider hard mechanical stops, either a stop on the ceiling or on the device or chains to limit the amount of travel with the appropriate signage. Both ends of the magnet should have these stops or signage.

Even with signage, there is nothing preventing from someone from accidentally unthreading the magnet. At N01/M01, someone has been injured because of this issue. Here is the signage on the N01/M01 magnets which became unthreaded, despite the signage:





4.0 Assembly

Stand Quality Control (QC):

- Check unassembled parts to print
- After assembly, check overall dimensions
- Check all adjustors for free movement and full range of motion
- Lubricate threads with Lubriplate or Chesterton 622 White Grease if needed. Verify with ES&H that the lubricant can be used in radiation environments since there are always concerns about mixed waste. (This is specifically why 622 White grease was used in the MI/RR tunnel. It is a food grade grease that has been approved by ESH&Q as to not cause a mixed waste if it becomes radioactive)
- Do not paint sliding surfaces or threads
- Verify with the engineer that QC has been completed before taking any stand parts or assemblies downstairs.
- If problems with any of the above are discovered, contact the Project Engineer for resolution.

5.0 Installation

Consider having templates for stand layouts made of aluminum or even cardboard. However, riggers and technicians often prefer to use the stand itself to use to use to drill the holes since the drill bit can walk or jump during hammer drilling. Aluminum templates can be made using drill bushings, which actually is even better than using the stand itself. This was done for Main Injector. It makes the job go quicker and holds the tolerances very well. One option to use with a template is a smaller pilot drill without a hammer drill to ensure that the hole is not

drilled at an angle. Then use a hammer drill for the final hole. This is not necessary with a drill bushing.

Rebar is typically $\frac{3}{4}$ " thick and has a spacing of 8" in tunnel hoops and 12" spacing for cast in place. This information will be specified on the FESS drawing but should not be counted on. The concrete strength can be assumed to be 3,000 psi for base material and 5,000 psi for shield blocks. If greater strength is needed for a design, check with a FESS engineer for the actual strengths, which will probably be greater than these very conservative estimates. The Hilti Scanner PS 50 can scan to 4.72" and costs about \$1500.

Rebar must be scanned prior to drilling concrete and hanging stands to allow for modifications if necessary. It has all of the specifics of how to scan, drill, set Hilti's and what types of anchors to use for different applications, as well as load-testing requirements.

Use unistrut embedments if possible (see information below). Check with FESS for specifications and load ratings.

For critical installations or with stands with not much vertical adjustment, one may want to consider mapping the floor or ceiling with survey's assistance to understand the straightness of the concrete.

Spalling concrete and old hilti holes are common in old tunnel enclosures. Additionally, old enclosure walls can have a significant angle (recently a wall was measured with a slope of about 3 degrees). Be aware that the concrete will probably not be uniform and perfect. Even with new construction, concrete walls and floors are usually level. Variations of +/- 1.5 inches in the level of floors in brand new buildings has been seen.

For some installations, the magnet must be lifted and temporarily supported, then the stand moved into place, then the magnet set on the stand. Provide clearance to move the stand in and out.

For magnets installed at a significant angle, provide angled fork adapters or other means of lifting the magnet into place and removing it at an angle, as was done on Muon Abort ABV2.

For magnets installed by means of trolleys or rails or roller skates, provide that the installation rails are structurally sound throughout the travel, and that the magnet can be set on and removed from the rail system by fork lift or magnet mover or chain falls or hydraulic lift table, as was done on NUMI Q106.

Concrete inserts:

Below is a catalog cut indicating the capacity of Unistrut P3200 series concrete inserts. As shown in attached data sheet, the allowable capacity for unistrut P3200 series inserts varies depending on the continuous length of the embedment.

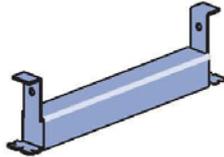
The Main Injector specified Unistrut P3200 series or Elcen Metal Products Figure 1150 concrete inserts in the general notes. No information was found for the Elcen concrete inserts. The Elcen web site only has information for pipe hangers. That said, it is likely

that the concrete inserts for Main Injector were Unistrut P3200 series. Unistrut P3200 series is also what the Mu2e drawings call for.

MEDIUM DUTY

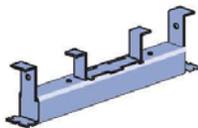
P3200 SERIES - 1 1/8" x 1 3/8"

P3249 thru P3252



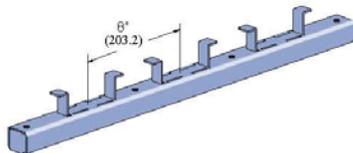
"NC" Suffix – No Closure Strip, With End Caps
 "WC" Suffix – With Closure Strip & End Caps

P3253

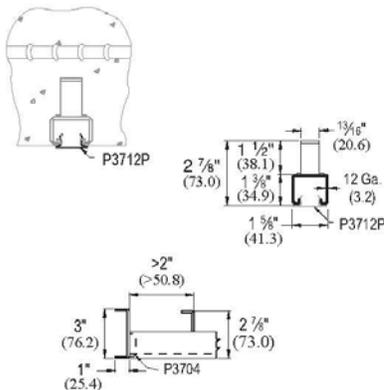


"NC" Suffix – No Closure Strip, With End Caps & Back Plates
 "WC" Suffix – With Closure Strip, End Caps & Back Plates

P3254 thru P3270



"NC" Suffix – No Closure Strip, W/End Caps & Back Plates
 "WC" Suffix – W/Closure Strip, End Caps & Back Plates
 "X" – No Closure Strip, No End Caps, W/Back Plates



FEATURES AND BENEFITS

- Includes closure and end caps unless otherwise requested
- P3280 end cap used when distance to first anchor is up to 2" (51 mm)
- P3704 end cap is used when end distance to first anchor is over 2" (51 mm)
- Nail or anchor inserts to forms every 16" (406.4 mm) to 24" (609.6 mm)
- Anchors are 8" (203.2 mm) on center
- Material: Cold formed from 12 Ga. (3) steel conforming to ASTM A1011 SS GR 33 or ASTM A653 GR 33. A. Stainless steel available on special order
- Finish: Choice of hot-dipped galvanized (HG) conforming to ASTM A123 or A153, or pre-galvanized (PG) conforming to ASTM A653-G90

***IN-STOCK NOW**

Part Number	Insert Length In/Ft (mm)	WT/100 pcs Lbs (kg)	Max. Allowable Point Load Lbs (kN)	Min. Spacing of Pt. Loads In (mm)	Max. Allowable Uniform Load Lbs (kN)
P3249	3"	85	500	—	500
	76.2	39	2.22	—	2.22
P3250	4"	100	800	—	800
	101.6	45	3.56	—	3.56
P3251	6"	130	1,000	—	1,000
	152.4	59	4.45	—	4.45
P3252	8"	159	1,200	—	1,200
	203.2	72	5.34	—	5.34
P3253	12"	227	2,000	—	2,000
	304.8	103	8.90	—	8.90
P3254	16"	270	2,000	12	4,000
	406.4	122	8.90	304.8	17.79
P3255	20"	357	2,000	12	4,000
	508.0	162	8.90	304.8	17.79
P3256	24"	399	2,000	12	4,000
	609.6	181	8.90	304.8	17.79
P3257	32"	527	2,000	12	2,000 Lbs./Ft. (kg/m)
	812.8	239	8.90	304.8	2,976.3 (kg/m)
P3257A	36"	616	2,000	12	2,000 Lbs./Ft. (kg/m)
	914.4	279	8.90	304.8	2,976.3 (kg/m)
P3258	40"	661	2,000	12	2,000 Lbs./Ft. (kg/m)
	1,016.0	300	8.90	304.8	2,976.3 (kg/m)
P3259	4"	786	2,000	12	2,000 Lbs./Ft. (kg/m)
	1,219.2	357	8.90	304.8	2,976.3 (kg/m)
P3260	5"	1,003	2,000	12	2,000 Lbs./Ft. (kg/m)
	1,524.0	455	8.90	304.8	2,976.3 (kg/m)
P3261	6"	1,173	2,000	12	2,000 Lbs./Ft. (kg/m)
	1,828.8	532	8.90	304.8	2,976.3 (kg/m)
P3262	7"	1,390	2,000	12	2,000 Lbs./Ft. (kg/m)
	2,133.6	630	8.90	304.8	2,976.3 (kg/m)
P3263	8"	1,560	2,000	12	2,000 Lbs./Ft. (kg/m)
	2,438.4	708	8.90	304.8	2,976.3 (kg/m)
P3264	9"	1,741	2,000	12	2,000 Lbs./Ft. (kg/m)
	2,743.2	790	8.90	304.8	2,976.3 (kg/m)
P3265	10"	1,947	2,000	12	2,000 Lbs./Ft. (kg/m)
	3,048.0	883	8.90	304.8	2,976.3 (kg/m)
P3266	12"	2,334	2,000	12	2,000 Lbs./Ft. (kg/m)
	3,657.6	1,059	8.90	304.8	2,976.3 (kg/m)
P3267	14"	2,717	2,000	12	2,000 Lbs./Ft. (kg/m)
	4,267.2	1,232	8.90	304.8	2,976.3 (kg/m)
P3268	16"	3,116	2,000	12	2,000 Lbs./Ft. (kg/m)
	4,876.8	1,413	8.90	304.8	2,976.3 (kg/m)
P3269	18"	3,530	2,000	12	2,000 Lbs./Ft. (kg/m)
	5,486.4	1,601	8.90	304.8	2,976.3 (kg/m)
P3270*	20"	3,882	2,000	12	2,000 Lbs./Ft. (kg/m)
	6,096.0	1,761	8.90	304.8	2,976.3 (kg/m)

Safety factor of 3

6.0 Analysis and Calculation Guidelines

Stand designs are often re-used within the Accelerator Complex and sometimes original (or unique) designs are necessary. In either case, before proceeding with a design, initial stress calculations are required. Primary stress and deflection estimates will indicate if a support is adequate or if reinforcement is needed. Weldments are another important consideration regarding stress evaluation.

The basic characteristic of primary stress is that it is not self-limiting, and failure, or at least gross distortion, can occur from one application of the loading. Primary stress is stress caused by the application of mechanical pressure, forces, and moments. Thermal stresses are not primary stresses.

Secondary stress is caused by the constraint of adjacent parts or by self-constraint of the structure, and yielding can cause the source of the stress to be eliminated. One load cycle can cause local yielding and stress redistribution but cannot result in failure or gross distortion. This document focuses on the primary stresses within the support design.

Allowable stress estimates for structural members, welds, and hardware are provided by the American Institute of Steel Construction (AISC) Manual of Steel Construction, Allowable Stress Design¹. The maximum primary stress shall be less than $0.6F_y$ (in bending or tension), $0.4F_y$ (in shear), where the Tensile Yield Strength (F_y) for A-500 structural steel is 46 Ksi and for A-36 steel it is 36 Ksi.

Stresses in Beams

Primary stresses within structures may be determined by considering a simple supported beam. This is an effective way to initially understand the stresses present for a given design. As the design progresses, a more detailed analysis may be considered which would include secondary stresses.

Normal Stress

A normal stress is a stress that occurs when a member is loaded by an axial force. The value of the normal force for any prismatic section is simply the force divided by the cross sectional area:

$$\sigma = \frac{P}{A}$$

σ – Normal Stress

P – Axial Force

A – Cross Sectional Area

A normal stress will occur when a member is placed in tension or compression. Examples of members experiencing pure normal forces would include columns, collar ties, support rods, etc.

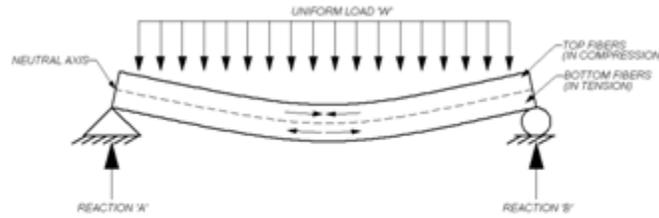


Figure 1-Beam diagram

When a member is being loaded similar to that in Figure 1, bending stress (or flexure stress) will result. Bending stress is a more specific type of normal stress. When a beam experiences load as shown in Figure 1, the top fibers of the beam undergo a normal compressive stress. The stress at the horizontal plane of the neutral axis is zero. The bottom fibers of the beam undergo a normal tensile stress. It can be concluded therefore that the value of the bending stress will vary linearly with distance from the neutral axis.

$$\sigma_b = \frac{My}{I}$$

σ_b – Bending stress

M – Calculated bending moment

y – Vertical distance away from the neutral axis

I – Moment of inertia around the neutral axis

Calculating the maximum bending stress is crucial for determining the adequacy of beams and longitudinal girders and stand members.

Shear Stress

Normal stress is a result of load applied perpendicular to a member. Shear stress however results when a load is applied parallel to an area. Figure 1 shows that both bending and shear stresses will develop. As in bending stress, shear stress will vary across the cross sectional area.

$$\tau = \frac{QV}{Ib}$$

τ - Shear Stress

Q - Calculated statical moment

V - Calculated shear at specific section

I - Moment of inertia around the neutral axis

b - Width of beam at depth of specific section

Calculating the maximum shear stress is crucial for determining the adequacy of beams and longitudinal girders and stand members. Or simply $\tau = F/A$, where F is the shearing force and A is the cross-sectional area.

A few examples for different situations regarding beams is given in Figures 2, 3, 4 and 5 with the relative equations needed to estimate reactions, moments and deflections.

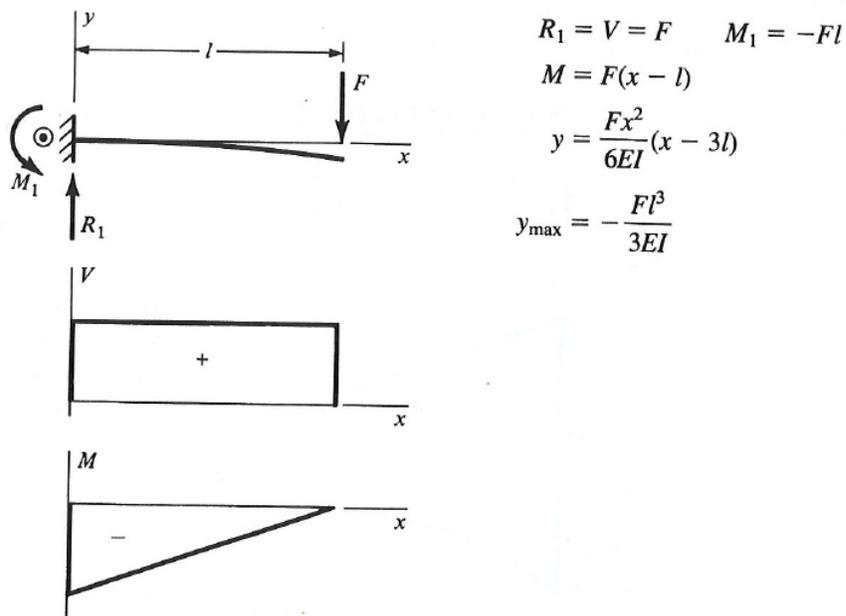
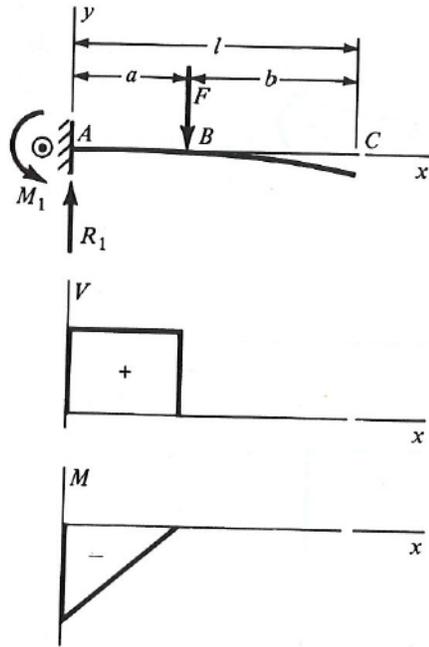


Figure 2: Cantilever beam (end loading)².



$$R_1 = V = F \quad M_1 = -Fa$$

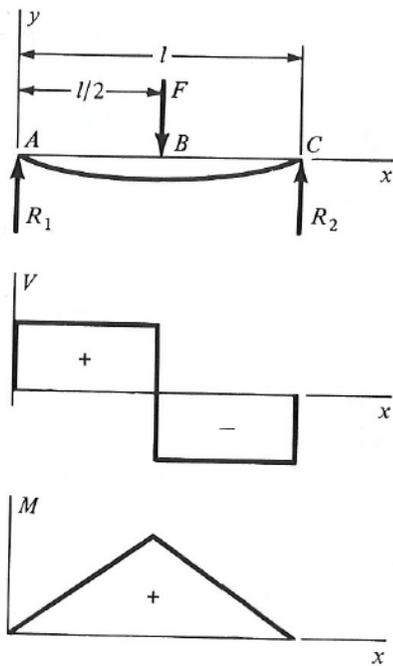
$$M_{AB} = F(x - a) \quad M_{BC} = 0$$

$$y_{AB} = \frac{Fx^2}{6EI}(x - 3a)$$

$$y_{BC} = \frac{Fa^2}{6EI}(a - 3x)$$

$$y_{\max} = \frac{Fa^2}{6EI}(a - 3l)$$

Figure 3: Cantilever beam (intermediate loading)².



$$R_1 = R_2 = \frac{F}{2} \quad V_{AB} = R_1$$

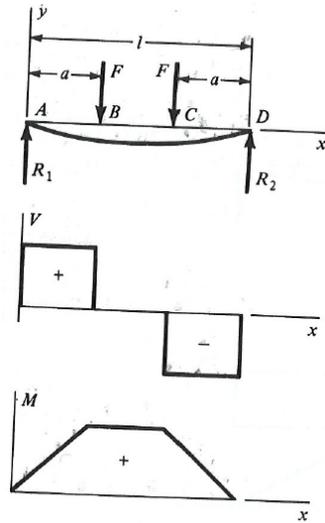
$$V_{AB} = R_1 \quad V_{BC} = -R_2$$

$$M_{AB} = \frac{Fx}{2} \quad M_{BC} = \frac{F}{2}(l - x)$$

$$y_{AB} = \frac{Fx}{48EI}(4x^2 - 3l^2)$$

$$y_{\max} = -\frac{Fl^3}{48EI}$$

Figure 4: Simple supported beam (center loading)².



$$\begin{aligned}
 R_1 = R_2 = F & \quad V_{AB} = F & \quad V_{BC} = 0 \\
 V_{CD} = -F & & \\
 M_{AB} = Fx & \quad M_{BC} = Fa & \quad M_{CD} = F(l-x) \\
 y_{AB} = \frac{Fx}{6EI}(x^2 + 3a^2 - 3la) & & \\
 y_{BC} = \frac{Fa}{6EI}(3x^2 + a^2 - 3lx) & & \\
 y_{\max} = \frac{Fa}{24EI}(4a^2 - 3l^2) & &
 \end{aligned}$$

Figure 5: Simple supported beam (twin loading)².

Weldments

Stresses within butt (with V-groove weld prep) and fillet welds may be estimated using a simplification of the weld's geometry as a line (along the weld path). Bending properties of fillet welds are found in Figures 6 and 7. The primary concern is shear in welds and secondary shear or torsion (produced by bending).

Shear stresses found in a weld are estimated by again applying $\tau = F/A$. The area used is given in either Figure 6 or 7, depending on the weldment geometry.

Bending stresses within a weld are estimated by again applying, $\sigma_b = M(y)/I$ and this basic expression may be modified to include the geometry parameters needed to apply the theory to welds represented as lines. Simply substitute $I = 0.707(h)(I_w)$ and apply the relevant expression given in either Figure 6 or 7. Properties of welding rod for allowable stress estimation is provided by AISC¹ or a few examples are given in Figure 8².

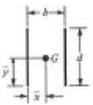
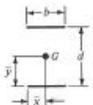
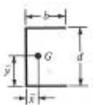
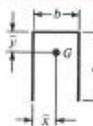
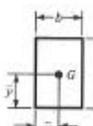
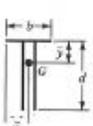
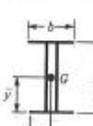
WELD	THROAT AREA	LOCATION OF G	UNIT SECOND MOMENT OF AREA
	$A = 0.707hd$	$\bar{x} = 0$ $\bar{y} = d/2$	$I_x = \frac{d^3}{12}$
	$A = 1.414hd$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_x = \frac{d^3}{6}$
	$A = 1.414hb$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_x = \frac{bd^2}{2}$
	$A = 0.707h(2b + d)$	$\bar{x} = \frac{b^2}{2b + d}$ $\bar{y} = d/2$	$I_x = \frac{d^2}{12}(6b + d)$

Figure 6: Bending properties of fillet welds (part 1)².

WELD	THROAT AREA	LOCATION OF G	UNIT SECOND MOMENT OF AREA
	$A = 0.707h(b + 2d)$	$\bar{x} = b/2$ $\bar{y} = \frac{d^2}{b + 2d}$	$I_x = \frac{2d^3}{3} - 2d^2\bar{y} + (b + 2d)\bar{y}^2$
	$A = 1.414h(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_x = \frac{d^2}{6}(3b + d)$
	$A = 0.707h(b + 2d)$	$\bar{x} = b/2$ $\bar{y} = \frac{d^2}{b + 2d}$	$I_x = \frac{2d^3}{3} - 2d^2\bar{y} + (b + 2d)\bar{y}^2$
	$A = 1.414h(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_x = \frac{d^2}{6}(3b + d)$
	$A = 1.414\pi hr$		$I_x = \pi r^3$

* I_x , unit second moment of area, is taken about a horizontal axis through G, the centroid of the weld group; h is weld size; the plane of the bending couple is normal to the plane of the paper and parallel to the y axis; all welds are of the same size.

Figure 7: Bending properties of fillet welds (part 2)².

AWS ELECTRODE NUMBER*	TENSILE STRENGTH, kpsi (MPa)	YIELD STRENGTH, kpsi (MPa)	PERCENT ELONGATION
E60xx	62 (427)	50 (345)	17–25
E70xx	70 (482)	57 (393)	22
E80xx	80 (551)	67 (462)	19
E90xx	90 (620)	77 (531)	14–17
E100xx	100 (689)	87 (600)	13–16
E120xx	120 (827)	107 (737)	14

*The American Welding Society (AWS) specification code numbering system for electrodes. This system uses an E prefixed to a four- or five-digit numbering system in which the first two or three digits designate the approximate tensile strength. The last digit indicates variables in the welding technique, such as current supply. The next-to-last digit indicates the welding position, as, for example, flat, or vertical, or overhead. The complete set of specifications may be obtained from the AWS upon request.

Figure 8: Minimum weld-metal properties².

I would recommend you add the table that shows torsional properties of welds as well, where $I = .707(h)(l_u)$ for bending is replaced with $J = .707(h)(J_u)$ for torsion. The bending equation does not change. The table will just list the J_u per weld pattern.

References

- [1] American Institute of Steel Construction, “Manual of Steel Construction – Allowable Stress Design,” 9th Edition, 1989.
- [2] Shigley, J. and C. Mischke, “Mechanical Engineering Design,” Fifth Edition, 1989.