Structural Support Design Guide

Document Category: Procedures

Division – Department: AD-MECHANICAL SUPPORT

ID:ED0011268 Revision: -

Revision Issue Date:

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Reviewer and Approver:	(Electronic Signatures and Dates on TC file) *

Revising Author:		**Date:**	

* Electronic Signatures and dates on Teamcenter (TC) item signoff report (Audit File)

REVISION HISTORY

REVISION	DATE	SECTION	REVISION DESCRIPTION

Contents

1.0 Purpose and Scope

The Structural Support Design Guide is a concise, functional reference for the design of structural supports typically utilized by the Mechanical Support (MSD) and Target Systems (TSD) Departments in Accelerator Division for accelerator equipment and similar devices. It captures institutional knowledge in MSD and TSD. Other departments/divisions/sections may also find this useful, but it is up to the individual using it to determine its relevancy toward specific applications. The Design Guide provides advice, best practices, load cases, examples, and links for the whole design process: design, analysis, fabrication, validation, installation, and final documentation. It is written in accordance with *FESHM 5100: Structural Safety, Work Smart Standards,* and *Fermilab's Engineering Manual*. Applicable codes and policies are referenced if a deeper dive is required.

Although this document is written as a reference for MSD/TSD design engineers, this advice applies to any "Non-Building Structures" as defined in Section 2.1. Supports subject to wind loading or requiring dynamic seismic analysis are beyond the scope of this document. Contact FESS Engineering for guidance with respect to civil engineering designs.

2.0 Requirements

2.1 Scope

At the highest level, requirements for structures flow down from FESHM 5100 (Structural Safety).

First, we must address which designs are classified as "Structures" within the scope of FESHM 5100. FESHM 5100 cites the International Building Code (IBC), which has a broad and vague definition of "Structures" that includes nearly everything we can imagine building at Fermilab. For the purpose of this guidance, we will consider two general classes of structures:

Building Structures
These are structures that feature any of the following:

- Intended to accommodate people as a primary function (e.g. buildings, rooms, bridges)
- Have their own connection to soil (foundation, footings, etc.)
- Are outdoors and subject to weather conditions
- Would ordinarily be the purview of FESS

These Building Structures are NOT the focus of this guidance. Generally, such structures should be designed in close collaboration with FESS, if not by FESS.

Non-Building Structures

All other structures can be characterized as Non-Building Structures (hereafter "Structures"), and are the scope of this guidance. These Structures include everything with any of the following features:

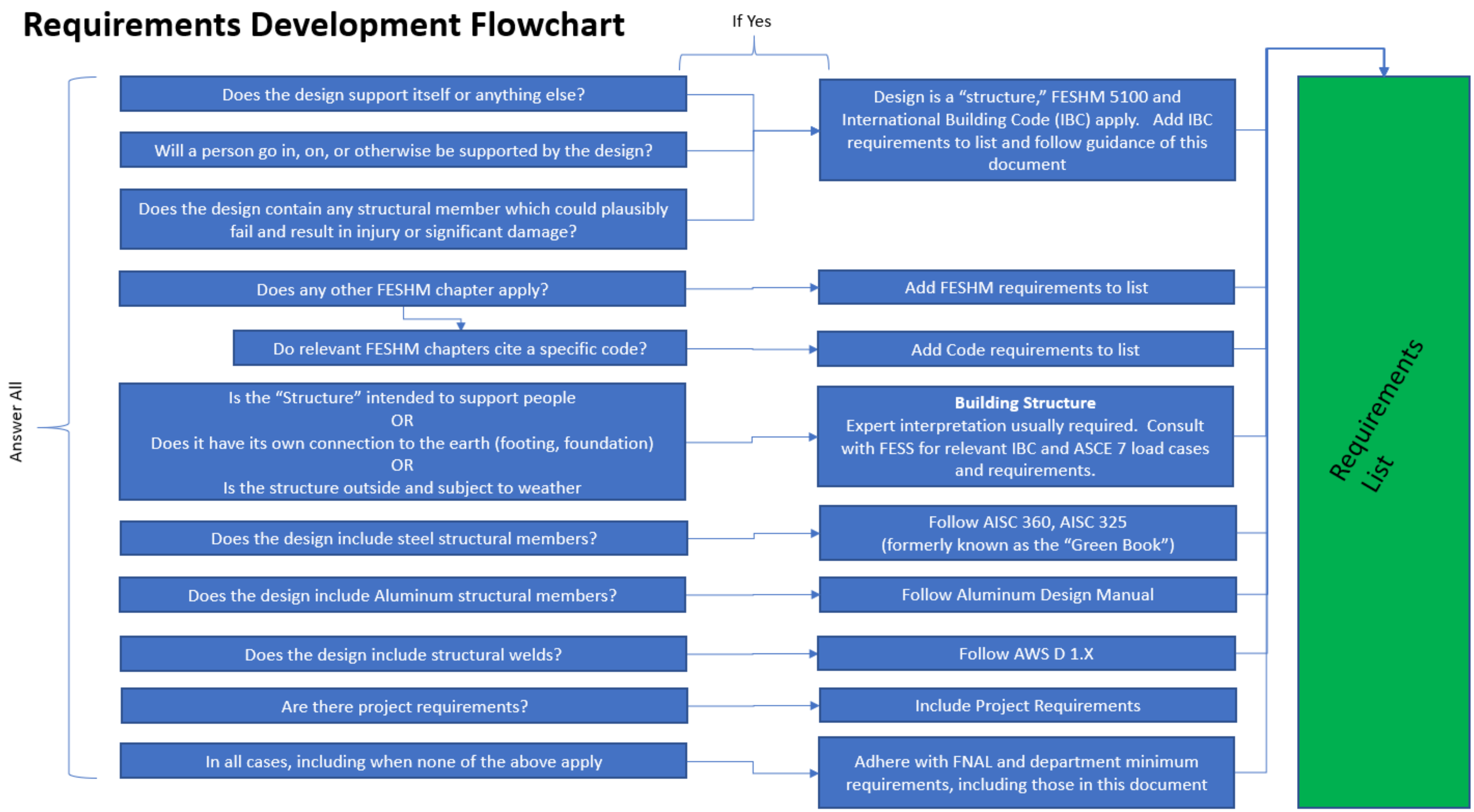
- The design carries non-trivial loads to support itself or something else
- A person could plausibly go in, on, or otherwise be supported by the design (including during installation, servicing, and operations scenarios)
- The design contains any structural members which could fail and result in injury or significant damage to equipment or property

Note that this definition is more broad than, and takes precedence over, previous MSD/TSD guidance for designs requiring a review. Anything that would have previously required an MSD/TSD structural design review still does.

2.2 Requirement Collection Method

For any structure design, there are FESHM, code, division/department and project requirements that may apply. The first step in design is to identify all relevant requirement sources and collect relevant requirements.

The following flow chart guides the collection of requirements. A requirement list should be compiled and documented for each design.


Requirements Development Flowchart
If Yes
Answer All
Does the design support itself or anything else?
Will a person go in, on, or otherwise be supported by the design?
Does the design contain any structural member which could plausibly fail and result in injury or significant damage?
Does any other FESHM chapter apply?
Do relevant FESHM chapters cite a specific code?
Is the "Structure" intended to support people OR Does it have its own connection to the earth (footing, foundation) OR Is the structure outside and subject to weather
Does the design include steel structural members?
Does the design include Aluminum structural members?
Does the design include structural welds?
Are there project requirements?
In all cases, including when none of the above apply
Design is a "structure," FESHM 5100 and International Building Code (IBC) apply. Add IBC requirements to list and follow guidance of this document
Add FESHM requirements to list
Add Code requirements to list
Building Structure
Expert interpretation usually required. Consult with FESS for relevant IBC and ASCE 7 load cases and requirements.
Follow AISC 360, AISC 325 (formerly known as the "Green Book")
Follow Aluminum Design Manual
Follow AWS D 1.X
Include Project Requirements
Adhere with FNAL and department minimum requirements, including those in this document
Requirements List

2.3 List of applicable FNAL Standards

The following FNAL standards apply to the design of structures, and may provide requirements that should be compiled in the Requirements List for a given design.

- Fermilab Engineering Manual
  - Includes requirements on the design and documentation process
- Engineering Risk Assessment
  - Required to complete for all structures
- FESHM
  - FESHM 5100 Structural Safety
  - FESHM 2110 International Contributions (International Codes & Standards)
  - Other chapters may apply to multi-purpose designs
- Prevention Through Design Approach (PtD)
  - Includes a method for defining lifecycle/operational requirements
  - Complimentary with Failure Mode and Effects Analysis (FMEA)
- Fermilab Radiological Control Manual
  - Includes requirements for design and configuration control of shielding
- QAM
  - Includes requirements for quality planning and documentation

2.4 List of Applicable External Codes and Standards

The following external codes may apply to the design of a given structure, and provide requirements that should be compiled in the Requirements List. Many of these are available through the Fermilab library.

- IBC
  - applies to all Structures per FEHSM 5100
- ASCE7
  - Includes load cases for Building Structures, requires significant civil expertise to interpret
- AISC 360/325
  - Steel structures
- Aluminum Design Manual
  - Aluminum structures
- AWS D 1.X
  - Family of codes applying to structural welding
  - Common applications at Fermilab include AWS D1.1 structural welding (steel), 1.2 (aluminum), 1.6 (stainless steel), 1.9 (titanium)

2.5 Project-based Requirements

A project may provide additional requirements for function or performance of a structure. It is a best practice for the design engineer to compile such requirements (if not provided by the project) and obtain approval from relevant project stakeholders. The Requirement and Specification Review process outlined in the Engineering Manual is an appropriate model for this.

2.6 MSD/TSD Design Requirements

The following Mechanical Support and Target Systems Departments minimum requirements apply to all Structure design. In case of conflict with any other source, the more stringent requirement applies.

2.6.1 Design

2.6.1.1 Load cases shall be defined per the method outlined in Section 2.7 and Appendix 8.1, and clearly documented with design documentation.

2.6.1.2 All Structure designs shall undergo a Failure Modes and Effects Analysis (FMEA). Optionally, this may be combined with a Prevention Through Design assessment. FMEA guidance and templates (developed for PIP-II, but broadly applicable) may be found in ED0013389.

2.6.1.3 All structures shall have an Engineering Risk Assessment per the requirements of the Fermilab Engineering Manual.

2.6.2 Tipping

2.6.2.1 Any design where tipping is possible shall undergo tipping analysis per the method outlined in Section 4.7.

2.6.2.2 Minimum tipping forces shall satisfy ALL the following criteria:

- Tipping force applied at the center of gravity of the component shall be >0.2*component weight for safety in seismic events.
- Tipping force applied to any plausible worst-case location shall meet both of the following criteria:
    - Tipping force shall be ≥ 200 lb regardless of component size/weight
    - Tipping force shall be > 0.1* component weight OR ≥ 5000 lb, whichever is less

  To clarify the interpretation of this, for even very small components tipping force should be >200 lbs (~scale of person applied loads). For the very largest components, tipping force should be >5000 lbs (scale of machine/accident applied loads).
- If an application has an expected tipping case loading scenario (e.g. proximity to a specific tipping force hazard), this scenario shall be explicitly analyzed.

2.6.3 Concrete Anchors

2.6.3.1 Concrete anchors shall be designed, installed and tested per the requirements of FESHM 7080.

2.6.4 Alignment

2.6.4.1 In the absence of more stringent project or design-based requirements, structures requiring coarse alignment shall permit alignment resolution of better than +/-5 mm in any degree of freedom.

2.6.4.2 In the absence of more stringent project or design-based requirements, structures requiring fine alignment shall permit alignment resolution of better than +/-250 μm in any degree of freedom.

2.6.4.3 All alignment stages shall incorporate hard stops or inspection holes to prevent driving an alignment feature to the point where it no longer restrains the payload.

2.6.5 Installation/Servicing/Operations

2.6.5.1 All components weighing ≥ 50lbs shall include explicit lifting/handling interfaces, which should be specified in the fabrication drawings.

2.6.5.2 All components weighing ≥ 30lbs shall have weight clearly labeled on the component, labeling should be specified on the fabrication drawings.

2.6.5.3 Lifting/handling interfaces shall be clearly labeled. If a dedicated lifting fixture exists, cross reference to the lifting fixture EN# is recommended.

2.6.5.4 All structures shall be clearly labeled with Teamcenter F# of either top-level or subassembly-level model/drawing number.

2.6.5.5 Any motorized/actuated component with travel speed >5mm/s shall have guarding to protect any pinch points.

2.6.5.6 For any preload-critical fastener, torque shall be specified on the drawing. Once torqued, fasteners shall be marked as such (for example, with a paint marker stripe across fastener head and substrate).

2.7 Load Cases and Combinations

2.7.1 Load Case Definition

IBC Chapter 16 provides guidance on load cases to consider, but is optimized for occupied structures such as buildings. Some interpretation is required to relate these to most Fermilab applications.

Please see Appendix 8.1 for a more thorough treatment of load cases, as well as margin recommendations when loads are only known to a preliminary level.

The IBC defines the following loads on structures:

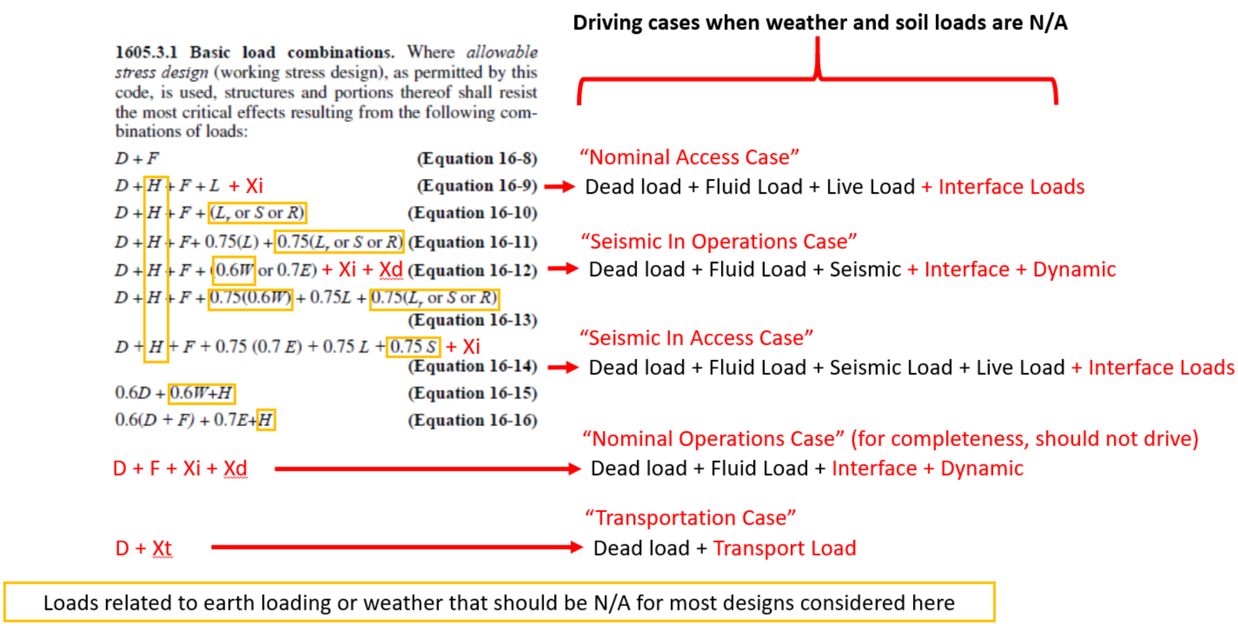
- D = Dead Load (Weight of the payload and the structure)

- F = Fluid Load (Fluid weight/pressure, which could potentially include vacuum loads)
- E = Seismic Load
  - Seismic requirements and calculation methods are elaborated in ASCE-7
  - For building structures at the Fermilab Site
    - Consult FESS: building structures are not within the scope of this document
    - Building structures at the Fermilab Site fall into Seismic Design Category A per ASCE-7 Chapter 11.7
  - For non-building structures and nonstructural components at the Fermilab Site
    - ASCE-7 does not require seismic load cases be applied to such structures
    - For conservatism, it is recommended to apply the ASCE-7 Chapter 11.7 Category A seismic load of 1% of dead load to non-building structures (Reference ASCE 7-16 Section 1.4.2)
    - Specifically, use E = 0.01g (i.e. 0.01*{D+F}) applied simultaneously in + or − X, Y and Z, with sign in each direction chosen to represent a worst case.
  - For structures to be installed at another site (e.g. SLAC), different site-specific seismic requirements may apply
  - See Appendix 8.2 for a FESS interpretation of seismic requirements for structures at the Fermilab Site
- L = Live Load (incidental and dynamic loading, including loads exerted by people)
  - See Appendix 8.1 for detailed guidance
  - For structures not primarily designed to support people, "handrail" loads may be used as horizontal loads, "catwalk" loads may be used for vertical loads
  - It needs to be determined whether concentrated or distributed loads are a worst case
- Xx = Special load (application-specific loads). Some common FNAL examples
  - Xi – loads applied at an interface, e.g. by bellows
  - Xd – dynamic loads not combined with personnel loads (e.g. moving structures)
  - Xt – transportation loads
  - Xa – accident loads, if a specific accident can be predicted

The design engineer will need to consider if other special loads are applicable to a design.

2.7.2 Load Combinations

IBC Chapter 16 prescribes how loads are to be combined for analysis. For example, Table 1605.3.1 provides load combinations to be used for allowable stress designs. These load combinations neglect some special loads that would be very common at Fermilab. They also include significant terms from earth/weather loading, which will be 0 for many FNAL designs (i.e. items located inside). As such, the following load cases should be considered when weather and soil loads are not applicable:



Please see Appendix 8.1 for greater detail and an example calculation. Following this method will provide combined loads that can be used to calculate stresses (specifically for Allowable Stress Design). For Load and Resistance Factor Design (LRFD), IBC prescribes comparable tables. See Section 4.1 for a discussion of Allowable Stress Design vs. LRFD.

2.8 Review Requirements

2.8.1 When you Need a Note

Given the broad scope of FESHM 5100/IBC, all Structures now require a FESHM Engineering Note. This requirement is more stringent than (and takes precedence over) previous MSD/TSD guidance for triggering a review. If you have read this far, you will need a note!

A FESHM note is required any time a structure will be installed, including prototype structures. In such cases, rev – of the note can be prepared for prototype structures, and later revs for production structures.

2.8.2 When you Need an MSD/TSD Review

As described above, all structures will now require a note that goes through technical review. This now defines the structure of the MSD/TSD (or any other) review process. For project-based structure design, it is a best-practice to initiate such reviews through the department to eliminate conflicts of interest between project deadlines and review rigor/timeline/result.

Reviews initiated through the Mechanical Support Department and Target Systems Department should be conducted per ED0000355 – AD/MSD FESHM Note Review Procedure.

2.8.3 Project Review Requirements

Projects may define their own review requirements for designs (PDR, FDR, etc.). The following considerations apply:

- The FESHM note review serves as the formal review for a structure, and is required whether or not there are project-based reviews.
- In the absence of project-defined review requirements, it is recommended that the Engineer organize project review(s) utilizing the graded approach of the Engineering Manual to ensure project buy-in with the design. Consultation with MSD department management and review coordinators can help to organize such reviews in a consistent manner.

3.0 Design Configurations

It is highly recommended to seek input from technicians and alignment personnel during the design phase. They are an invaluable resource to providing feedback on designs for ease of assembly/installation and alignment.

3.1 Architecture

Stands that support devices can be floor mounted, wall mounted, or ceiling mounted. **Concrete anchor selection, installation, and testing must adhere to FESHM Chapter 7080. Manufacturer guidelines are good design references and should always be followed.**

3.1.1 Floor Mounted

Floor mounted stands are the only types that allow for drop-in anchors. It is acceptable to use wedge-type, or expansion, anchors but these can cause a tripping hazard once the stand is removed. It’s not common but grout can be used with floor mounted stands in case a specific flatness is required. A recommendation is to verify the floor height before fabrication of a stand. It is known that the floor can be higher or lower than planned.

3.1.2 Wall Mounted and Ceiling Mounted

Wall and ceiling mounted devices must be fastened with expansion type anchors. If the stand and device are light enough, and the install location is at a spot with embedded Unistrut, then it can be attached to the embedded Unistrut. “Drop-in” style anchors shall not be used for these applications. Adhesive anchors may be suitable in limited applications.

The embedded Unistrut typically used at the lab is P3200 series and has a maximum allowable point load (per the manufacturer) of 2,000 lb and a maximum allowable distributed load of 2,000 lb/ft. The specifications and allowable loading of the embedded Unistrut should always be verified with FESS Engineering.

Example of Embedded Unistrut

3.2 Support Configurations and Alignment

There are three primary support configurations for devices: 6-strut kinematic, 3-point, and 4-point, .

3.2.1 6-Strut (Kinematic)

6-strut stands are statically determinant structures where the payload is supported by exactly 6 struts whose ends are rotationally free. In this configuration, each strut only takes axial load. Quasi-orthogonal adjustments may be achieved by the common “3-2-1” configuration:

- 3 struts oriented vertically (with the gravity load)

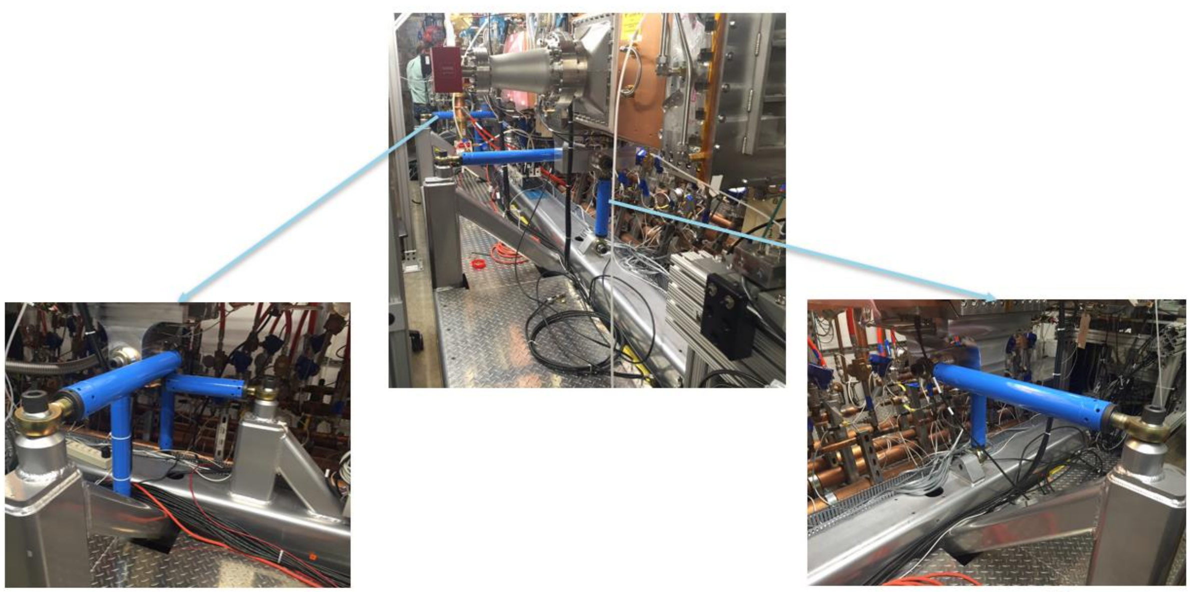
- 2 struts oriented transversely (usually left/right)
- 1 strut oriented longitudinally

Within each group, struts are nominally parallel. Between groups, struts are nominally perpendicular. This configuration facilitates alignment by minimizing cross-talk between degrees of freedom.

Other statically-determinate strut orientations are possible, for example the "hexapod," where struts are non-orthogonal. These arrangements can have better stiffness properties, but at the expense of cross-talk between alignment degrees of freedom and less intuitive adjustment.

With a 6-strut configuration, one must take care not to create an under-constrained (and therefore unstable) configuration. If any one strut is removed from a 6 strut stand, even (for example) a longitudinal strut that nominally carries no load, the whole stand can become under constrained and fall over.

Similarly, if one configures a 6-strut stand with 4 parallel struts (rather than the theoretical maximum of 3), the stand will be under constrained and will fall over. For a 6-strut stand design, one should walk through six orthogonal load cases (Force along X, Y, Z, Moment about X, Y, Z) and confirm that each load is properly reacted in the struts. A four-parallel-strut stand will fail this check.



A 3-2-1 orthogonal 6-strut mount (PIP-II RFQ), and strut grouping

A hexapod non-orthogonal 6-strut mount (Image credit: Ethan Arnold)

3.2.2 3-Point

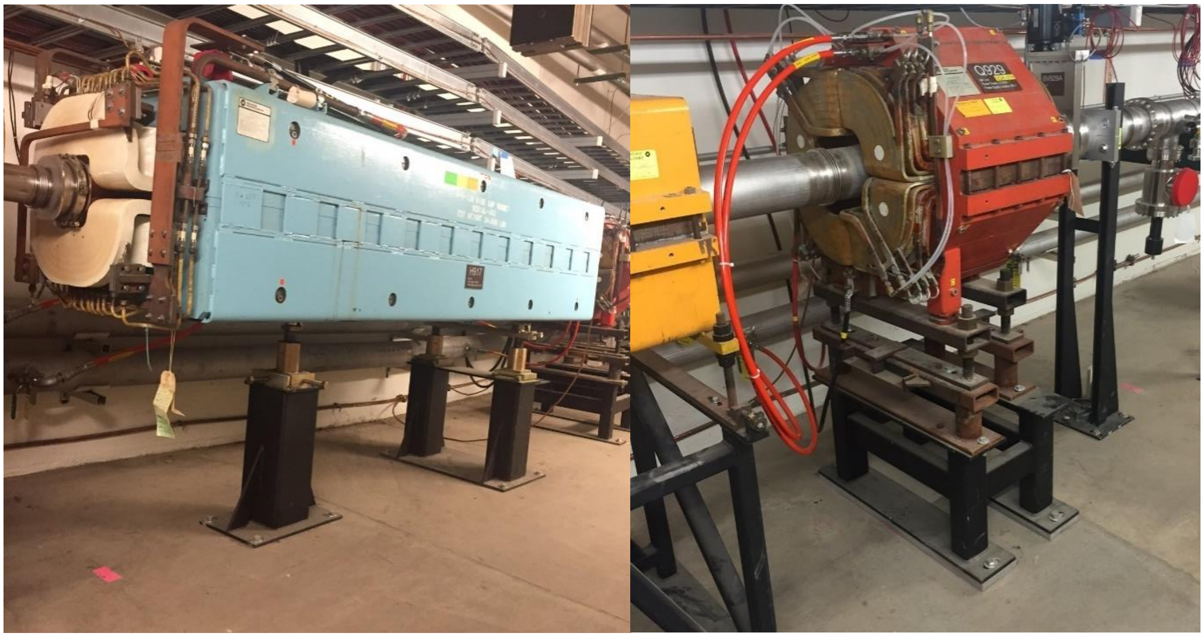
The three-point support is preferred by alignment, but there is an increased risk to tip over for engineers to keep in mind. Three-point stands are preferred for more accurate alignment, since for a 4-point stand, the weight distribution shifts among the four points as the magnet is adjusted. See section 4.7 for tip over analysis.

3.2.3 4-Point

Four-point supports are more difficult to align. This configuration decreases risk for tip over but must be analyzed keeping in mind that only three out of the four points are taking the load. Three-point adjustment on four-leg stands should be used, unless there is a good reason that a single adjuster cannot be used on one end, such as on a Lambertson or other unique magnet, on which a 4-point stand could be used.

3.2.4 Gravity-based or Restrained (for 3- or 4-Point Supports)

Gravity-based is a stand design (usually in the form of a ball foot and a receiving cup) that relies on gravity to keep the stand in place and does not have anything to secure it to the structure. This design has risk for tip over and must be analyzed to see what minimal force is required to initiate tip-over (see Section 2.6.2). Restrained stands have something holding the device in place to the structure. This could be either a bolted connection (struts/bolts), welded, or strapped down. Regardless, there is some positive retention force in play.



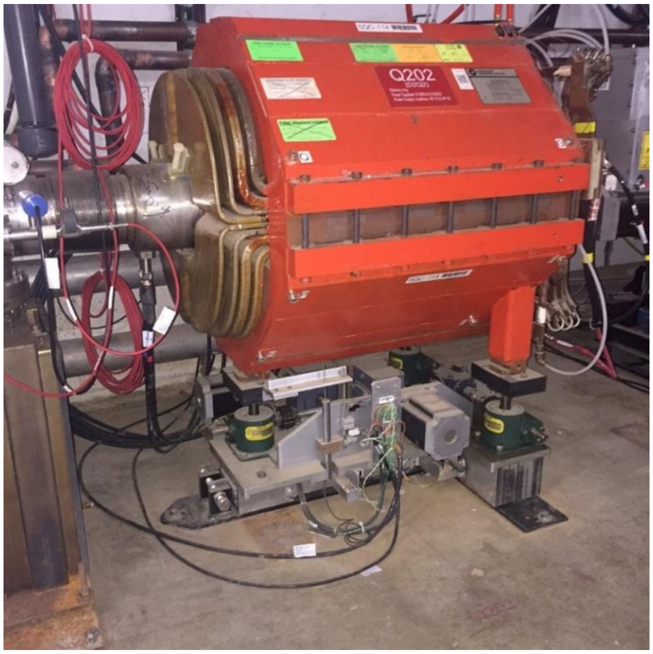
Examples of Gravity-based Stands

3.2.5 Alignment Considerations

Stands are required to have adjustment in the vertical and transverse directions. Some common methods for adjustment are with threaded rods and swivel nuts, 6-strut stand design, or gravity-based ball-cup. Fine longitudinal adjustment is required when projects deem it necessary. Coarse longitudinal adjustment can be done with slots in the floor plates. A good rule of thumb is to allow ±1 inch of adjustment. Blind hole adjustments are not allowed and must require a hard stop and a sight hole to verify that a hard stop is present.

3.3 Dynamic or Motorized Stands

Some designs require the device to be on motorized stands. Engineers must verify that weights fall within load limits of motors, screw jacks, gear worms, couplings, etc. Also, limit switches along with hard stops must be in place to prevent any unwanted travel. Failure Modes and Effects Analysis (FMEA) is strongly recommended for all dynamic structures.



Example of a Motorized Stand

4.0 Analysis

During component design, an engineer must ensure that the component they are creating can handle any reasonable load it may experience without failure, undesirable deformation/deflection, or performance degradation. This step of analyzing the structural integrity of the design is necessary to ensure safety of the design during manufacture, installation, and service. What follows is a set of considerations the engineer must make and how to perform a rigorous analysis of the stress on a design.

4.1 Allowable Stress Design vs. Load and Resistance Factor Design

Chapter 16 of the IBC contains the governing requirements for structural design and analysis. The general requirements of this chapter include the following:

"**1604.1 General.** Building, structures and parts thereof shall be designed and constructed in accordance with *strength* design, *load and resistance factor* design, *allowable stress design*, empirical design or conventional construction methods, as permitted by the applicable material chapters and referenced standards."

"**1604.2 Strength.** Buildings and *other structures*, and parts thereof, shall be designed and constructed to support safely the *factored loads* in load combinations defined in this code without exceeding the appropriate strength *limit states* for the materials of construction. Alternatively, buildings and *other structures*, and parts thereof, shall be designed and constructed to support safely the *nominal loads* in load combinations defined in this code without exceeding the appropriate specified allowable stresses for the materials of construction."

For the (mostly metal) structures on which this guidance document is focused, the permissible analysis methods are Allowable Stress Design and Load and Resistance Factor Design (LRFD), which the IBC defines as follows:

"ALLOWABLE STRESS DESIGN. A method of proportioning structural members, such that elastically computed stresses produced in the members by *nominal loads* do not exceed *specified* allowable stresses (also called "working stress design")."

"LOAD AND RESISTANCE FACTOR DESIGN (LRFD). A method of proportioning structural members and their connections using load and *resistance factors* such that no applicable *limit state* is reached when the structure is subjected to appropriate load combinations. The term "LRFD" is used in the design of steel and wood structures."

In general, Allowable Stress Design ensures safety by mandating that analyzed stress be less than or equal to an established allowable stress. The allowable stress is typically significantly less than the typical yield stress or capability of the material in question.

Load and Resistance Factor Design ensures safety by applying a load factor to expected loads (generally >1), a resistance factor to material strength or performance (generally <1), and demonstrating that in worst-case combinations no undesirable limit state (e.g. failure, excessive deflection) is reached. The code considers both serviceability limit states, where intended function is degraded, and strength limit states, where safety is compromised.

The IBC and the material-specific codes it references are prescriptive in the parameters and methods to be used for either design analysis method.

Allowable Stress Design is much more commonly used at Fermilab than LRFD.

Note that the IBC and referenced codes specify maximum deflection limits for structural members, deflection should also be assessed as part of a complete stress analysis.

4.2 Stress Analysis

Accurately calculating the stress on a component is the most important step in structural analysis because nearly every decision about the safety of a component is based on an accurate assessment of the stress on it. An engineer must be sure that their stress analysis considers every reasonable load that a component may encounter, and what effect that load will have on the component. These loads could be static, occasional, or dynamic. See Section 2.7 for different load cases and combinations. As an example, a static load might be the weight of an accelerator component on a stand. An occasional load might be the additional load of a lifting fixture attached to the component when it is being installed on the stand. A dynamic load would be the load imparted on a stand due to acceleration during an earthquake, or when a technician is standing or walking on a component. An engineer's job is to ensure that each of these scenarios is accounted for in a stress analysis.

Depending on the details of the design in question and the governing code(s), stress may be computed by formula, or by analytical or numerical methods such as Finite Element Analysis (FEA).

4.3 Weld Analysis

All welds in a structure must be analyzed to ensure that they do not pose a hazard. In performing this analysis, an engineer must refer to the drawings of the structure for the dimensions and configurations of the welds. The symbols in the drawing will call out parameters such as weld and groove type, weld length, root opening size, intermittent weld callouts, and other parameters. This information can be used to determine the throat area of the weld, which is commonly used to determine weld stresses in many scenarios. Welds can be loaded in the transverse or parallel direction, and generally experience both shear and normal stresses as a result. The AWS codes governs the design and analysis of welds. In addition to the weld itself, it is also important for an engineer to analyze the base metal near any welds for stresses, as these areas can sometimes be a more likely failure point than the weld itself.

4.4 Fatigue Analysis

Exceeding the immediate yield or tensile stress of a material is not the only way to fail it. A high number of repetitive or cyclical loads can fail a part through fatigue. With some materials there is a stress limit, called the fatigue or endurance limit, below which fatigue failure is not likely to occur. Designing a part to remain below the fatigue limit in these cases is one robust way to ensure safety against fatigue failure. When the stress in a material exceeds the fatigue limit of a material, or when dealing with materials that have no fatigue limit, the engineer must consult a published "S-N" chart to determine how many repetitive cycles a material can withstand at a given stress. It should be noted that S-N charts are probabilistic, and often based on relatively small sample sizes. One needs to understand the specific statistics of a given chart to interpret it correctly.

Severe fatigue conditions are not common in Fermilab structural support applications, but may be encountered in flexure motion elements, rotating equipment, and equipment subjected to pulsed thermal or mechanical loads.

4.5 Fastener Load Analysis

Fasteners and threads need to be analyzed as individual components in an assembly to ensure that they will not fail in either the bulk material or through thread stripping. A few important considerations should be made when designing and analyzing bolted joints.

Fasteners can be purchased in several different material strengths, classified as "grades" for imperial fasteners (e.g. grade 2, grade 5, grade 8) and "classes" for metric fasteners (e.g. class 10.9, 12.9). Care is required to ensure that a consistent grade/class is used in design, specification, analysis, procurement, and installation. At every fastened joint, the weakest link of the joint should be assessed and understood.

If the joint that is to be fastened will experience shear, it should ideally be designed such that the friction at the clamped joint interface or a separate shear feature handles the shear load, rather than the fastener itself.

If a clamped joint will undergo cyclic loading, it is desirable to clamp the joint with a preload significantly higher than the cyclic stress. In a properly designed joint, this will eliminate gapping at the joint and reduce the amplitude of the cyclical stress the fastener experiences, and maximize the fatigue life of the joint.

When installing fasteners, thread lubricant affects how much tensile preload is established for a given fastener torque. In general, a lubricated fastener will require less torque and achieve a more predictable preload than an unlubricated fastener. The engineer must consider this when writing fastener assembly instructions. In addition, some assemblies may require a specific torquing procedure to be followed (such as vacuum flanges).

In summary, the engineer must accurately analyze each fastened joint to determine exactly how much tensile and shear load is applied to the fasteners. For commercially available structural fasteners, material-specific governing codes provide allowable loads and analysis prescriptions.

4.6 Buckling Analysis

For material under compression, buckling is another important failure mode to consider. Despite being able to handle a compression load from a yield stress perspective, a component under compression can still fail through an instability called buckling, where a member bends until collapsing in on itself. The force required to cause buckling in a part depends on many factors such as load geometry, material choice, cross sectional shape and size, and how the part is attached to the rest of the structure (also known as the end condition). When performing a buckling analysis on a heavy member, it is also important to consider the member weight's contribution to buckling failure. For analyzing and designing members subject to buckling failure, refer to the governing code. These codes are material specific and can be traced from the IBC.

4.7 Stored Energy

Component and stand assemblies can contain stored energy in many different forms. The most common form (discussed more below) is gravitational potential energy. Some assemblies may also store mechanical energy in the form of compressed or stretched springs, compressed hydraulic fluid, compressed gas or evacuated volumes (vacuum systems), electrical energy, magnetic field energy, or other forms of energy. It is important to characterize and quantify all forms of stored energy, and to determine their hazards and effects on the structure. An engineer may need to modify their design to mitigate or eliminate these hazards.

Stored gravitational potential energy is common to all stand assemblies, and its danger must be assessed by performing a tip-over analysis. An assembly can be unsafe if it contains stored gravitational potential energy that can be released in an uncontrolled manner. At Fermilab, the most common example of this is a heavy component resting on a stand without fastening or hold-down provisions. Often, components rest freely on an adjustment assembly that has 3 points of contact with the component. These 3 points provide vertical support forces, but do not prevent the component from lifting off of them. This makes component installation on the stand simple, but it also means that the stand does not prevent component tipping. As a result, the engineer must analyze how difficult it is to tip the component off the stand and ensure that this is acceptable from a safety standpoint. To aid in this analysis, a paper has been written and stored in Teamcenter as item ED0006799. Also stored in this item is an Excel spreadsheet that can aid the user in calculating 3-point stand tipping forces.

4.8 Structural Safety During Fabrication, Transport, and Installation

In addition to its final state, all the intermediate states of a structure during fabrication and assembly must also be structurally sound. This may require temporary reinforcement or additional material that might otherwise be unnecessary when only considering the final product. It is extremely important that the engineer carefully consider the entire lifecycle of a design and determine whether there ever exists an unsafe structural condition in that lifecycle. Situations worth considering include the loads and forces present during fabrication, assembly, transport, installation, alignment, maintenance, and decommissioning.

5.0 Fabrication Considerations

5.1 Design for Manufacturability

Some designs look great on paper but are either impossible or prohibitively expensive to manufacture. It should be feasible to fabricate the part with available machining methods. Following the guidelines below will prevent adding unnecessary fabrication time and cost to the job.

- Consider using weldments in lieu of parts hogged out of billet material. This strategy is often easier to manufacture and can save considerable cost.
- Incorporating appropriately sized lateral bracing or members with moment connections in a design is often preferable to adding gussets.
- Standard counterbores have standard sized drills. If a nonstandard sized counterbore is called out, the counterbore needs to be milled out, adding an extra machining operation.
- Tolerances should be reasonable to fit the purpose of the part. This is relevant when using plates or other stock material that might bow or deform when skin is removed or the material is otherwise cut. Ordering larger pieces is advisable if part tolerances are tight.
- Specify tolerances only as tight as needed. Overly tight tolerances result in unnecessary machining operations, adding cost and time to the job.
- Stock sizes in material callouts should be checked for availability. When specific materials are required, use the full material designation.
- Make through slots if possible to avoid EDM on a slot that doesn’t go all the way through the thickness of the material. Alternatively, a two-piece plate can be made.
- Pick one edge or a corner to dimension from. It makes it much easier for the machinist and reduces mistakes. Dimension to the center of slots.
- Add radii to tight corners.

- Verify that the material has been called out correctly, postprocessing notes are included, and that the drawing is approved.
- Consult MSD's Fabrication and Procurement Group for information about plating and coating. They can help with industry specs, types and classes, thickness range, material, and other information.

MSD's Fabrication & Processing Specialists or a machinist can advise on tolerancing, finish, and features to aid fabrication.

5.2 Design for Assembly

Tolerance stack-ups are vital to address mechanical fit and performance requirements. Geometric Dimensioning and Tolerancing (GD&T) is a powerful tool for managing tolerance stack-up. Many opportunities are available for GD&T training.

5.3 Design for Installation and Service

Proper fit is critical for a smooth installation. Good modeling with a layout fit check with a verified coordinate system is helpful for tight spots. Virtual reality provides a good platform to verify that there is access for tools and personnel during assembly and installation. It can be helpful to ask Alignment and Metrology Department experts for advice when designing adjusters on supports for fine-tuning of position.

Storyboards are an excellent way to visualize the installation process by breaking down a big job into specific segments over time. It allows for closer analysis of all the steps.

Installation efficiency can be improved by mounting several devices on a single girder. This can be done outside of the tunnel, and the whole assembly can be moved into place at the same time.

Supports for high radiation areas should be designed such that radiation exposure is ALARA (**A**s **L**ow **A**s **R**easonably **A**chievable)[1] for the entire installation process, including alignment and attachment of the device being supported. For other considerations concerning high radiation areas, see Section 7.1.

Plans for future repairs and upgrades should be accounted for in the design.

5.4 Recommended Materials and Practices

Radiation produced by accelerators can degrade materials and cause failures early in the service life of a part. Most plastics become brittle and many electronics fail over a short period of time in this environment, so they are not recommended for use in or near beamlines. High strength steels have also failed in corrosive or extremely high radiation areas due to hydrogen embrittlement. Solid state

[1] Fermilab Radiological Control Manual, https://eshq.fnal.gov/manuals/frcm/

electronics are particularly problematic. Remotely actuated supports that include electronics, lubricants, nonmetal seals, and other parts that will be used in radiation areas should be chosen carefully.

Electron accelerators often require low magnetic permeability materials near the beam to minimize undesirable effects on beam performance. Welding and cold work machining processes should be carefully specified to keep the permeability low, as these processes can increase it locally. Minimizing cold work during machining and minimizing heat affected zone during welding are helpful, as is choosing a filler rod that has low magnetic permeability. Low permeability stainless steels and aluminum are typically used for beamtube supports in these areas.

5.5 Welding Considerations

5.5.1 Quality Control

The most common nondestructive tests used at Fermilab are visual inspection, radiography, and dye penetrant. Dye penetrant tests can be done at Fermilab; other testing is contracted out. If welding is performed at an outside vendor, the vendor and engineer should specify acceptance criteria and weld testing to be done by the vendor's QC. Certification should be provided.

5.5.2 Code Compliance

AWS D 1.X and other welding codes offer requirements for weld design, welder qualification, weld inspection, and more that are relevant to work planning.

5.6 Coatings and Surface Processing

Coatings and surface processing can be added for protection from environment (humidity, chemicals, etc.), function (friction coefficient, etc.), and aesthetics. Value engineering principles provide guidance when choosing between costly and economical coatings/processes. Pre-treatments, cleaning prior to coating, and surface protection should be clearly specified in purchase requisitions for best outcomes. Proper fixturing should be designed or specified with the vendor; poor fixturing can result in coating nonuniformity and deformation of parts, among other problems.

5.7 Procurement

The bidding process for outside jobs typically takes at least six weeks, not including the time that it takes for a purchase order (PO) to be issued after submitting a requisition (that is often an additional four weeks or more). This can take even longer for high cost or specialty jobs. If a sole source is appropriate, it should be included with the requisition, however this does not always guarantee that the bidding process will be avoided.

Potential vendors can be identified through Procurement Specialists and Fabrication & Processing Specialists, and a site visit can be helpful in confirming a good fit. It is recommended to follow up with the Procurement Specialist and vendor throughout the procurement/manufacturing process until PO requirements are fulfilled.

6.0 Installation, Validation, and Final Documentation

6.1 Installation Work Planning

All installation work activities shall be subject to work planning and control as outlined in FESHM 2060. Fermilab's work planning and controls process utilizes SHAPE (**S**cope, **H**azard, **A**uthorize, **P**erform, **E**valuate), a continuous process of work as shown in Fig. 6.1, where all aspects of SHAPE are continually evaluated throughout the entire work process. All personnel involved with the installation are responsible for working within the parameters of SHAPE. Refer to the ESH Work Planning and Control website for latest updates and more details.

Figure 6.1 Fermilab SHAPE Work Planning and Control Process

As stated in FESHM 2060, work planning ensures that the scope of work is understood, appropriate materials and equipment are available, all hazards have been identified, mitigation efforts established, and all affected personnel understand what is expected of them. The hazard analysis process is a critical part of work planning. The work planning and control process shall include proposing the work and defining the **S**cope of the work, identifying **H**azards and controls, **A**uthorizing the work to commence, **P**erforming the work, and post work **E**valuation. The careful planning of work will assure that it is performed efficiently, safely, and on schedule.

The **I**ntegrated **M**anagement **P**lanning **& C**ontrol **T**ool (IMPACT) should be used as a one-stop shop for the most frequently used work planning tools, such as Hazard Analysis (HA). Refer to the ESH IMPACT website for latest updates and more details.

For radiological work, refer to the Fermilab Radiation Control Manual (FRCM) for requirements related to working in radiation areas. If an ALARA plan is required, then the lead engineer first develops the dose plan based on the installation details (often requiring a detailed installation procedure), from which radiation safety then generates the ALARA plan.

FESHM/QAM Chapters to be considered during installation include, but may not be limited to:

FESHM 2001 – Environment, Safety & Health for Projects

FESHM 2060 – Work Planning & Control/Hazard Analysis

FESHM Chapter 2100 – Fermilab Energy Control Program (Lockout/Tagout)

FESHM Chapter 4130 – Personal Protective Equipment (PPE)

FESHM Chapter 7040 – Concrete Cutting and Coring Activities

FESHM Chapter 7080 – Concrete Anchor Devices

FESHM 10200 – Lift Plans

FESHM 10130 – Slings and Rigging Hardware

QAM 12002 – Fermilab Quality Assurance Program

QAM 12100 – Incoming Inspection and Acceptance

QAM 12010 – Lessons Learned Program and Procedures

QAM 12020 – Suspect/Counterfeit Items (S/CI) Program

An important aspect for completing installation work in an efficient and timely manner is good communication between all stakeholders (installation coordinator, machine departments, and the various support departments – alignment, instrumentation, EE support, etc.).

6.2 Important installation considerations

In addition to SHAPE, the following questions/considerations need to be addressed before commencing the installation work:

- Are the correct resources/skill sets available to complete the installation work?
- Are there any special rigging requirements or special equipment needs? For example, installing magnets at an incline will require specialized equipment for magnet transport and installation.
- How will the work fit within other concurrent installation work, how long will it take, are there any schedule or external (project) requirements, and are there any external resources needed?
- Consider installation planning and logistics such as selecting and securing needed equipment, transport and staging of equipment, space requirements, etc.
- Procedures – assess whether you need one, usually needed for critical installations or for developing an ALARA plan.
- Identify installation interfaces with different groups/individuals – work with the installation coordinator; check the CAD integration model.
- Use Virtual Reality to identify problems ahead of time.
- Installation drawings should be finalized before commencing installation work (drawings need to be checked and approved). Drawings should be printed and provided to everyone, and if possible pasted at the installation site.
- Field changes – define the process of handling field changes. Run field changes through the lead engineer (plus stake holders/interfacing systems as needed).
- Concrete anchor installation and load testing – refer to FESHM 7080. Holes should be large enough for the drill bit with sufficient space for the drill tool. Include extra holes in case you hit rebar and understand how to do the load test in the space available. Scan for re-bar prior to drilling in concrete. In addition, look out for spalling concrete and old anchor holes which are common in existing tunnel enclosures. Also note that concrete walls and floors are usually not level due to civil construction tolerances.
- Always refer to FESS Engineering on concrete strength and allowable loads.

6.3 Testing & Validation

Concrete anchor use requires adherence to FESHM 7080. Ensure that there is adequate space available to do the load test.

Load tests of ceiling and wall mounted support structures shall be conducted at 125% of their rated capacity after final installation (refer to FESHM 10110, Section 4.4 - Testing). This ensures that every component in the load path is load tested to the 125% requirement. The point of load application should mimic the actual load case as closely as possible. The design engineer needs to review and approve the methodology and process for conducting the load test.

Conduct walk-throughs to ensure all support systems and components are installed to the design requirements and specifications and that there are no safety hazards.

6.4 Release to Operations & Final Documentation

Release to operation and final documentation should follow the guidelines of the Fermilab Engineering Manual. All drawings should be updated to the as-built status. Photos should be taken during the installation process, especially for critical installations or installations requiring a procedure, and these photos should be included as part of the as-built documentation.

As part of the Evaluate process of SHAPE, there needs to be a post-job debrief of lessons learned, and the work plan and HA updated accordingly. QAM 12010 (Lessons Learned Program and Procedures) establishes the responsibilities and actions required to process and communicate lessons learned.

7.0 Special Applications

7.1 High Radiation Environment Considerations

Special consideration needs to be given to structural support systems designed for high radiation environments. Ionizing radiation in humid air produces nitric acid and ozone, plus free hydrogen and oxygen, which can lead to accelerated corrosion of structural elements including fasteners. Therefore, it's important to take into consideration the gas medium and resulting radiolytic products, together with the thermal energy deposition (EDEP) from the interacting beam.

Years of operating the MiniBooNE and NuMI facilities has led to several lessons learned, the following items summarize some of these special considerations when designing for high radiation environments:

1. Use of high strength steel fasteners (e.g. Grade 8) is prohibited in target facilities where beam is directly interacting with air as it strikes target materials or beam elements further downstream. The beam will dissociate water vapor into hydrogen and oxygen, letting free hydrogen embrittle high strength steel alloys. The threshold for embrittlement has been shown to be HRC 35 or harder. Standard target facility fastener use should consist of stainless steel or titanium grades only. A500 structural steel and lower yield strength structural grades can be used in target facility environments without issue.
2. In addition to stress, deformation, and fatigue, target facility structural elements must be analyzed to understand the following:
    a. Thermal considerations if near the beam spray (high EDEP) and uncertain cooling conditions
    b. Thermal stability during operations (thermal expansion after alignment)
    c. Vibration mode shapes
    d. Buckling
    e. Material interfaces (galling, spalling, corrosion, galvanic coupling)
3. Account for weld distortion when dealing with fabrications with critical or difficult to align features. For example, pads or support surfaces can be built with extra material and post-machined to achieve the desired geometric tolerance requirements. Consult a reliable reference on controlling weld distortion for more complicated weldments
4. All mounting points for stands should have holes provided that allow an anchor drill bit to fit through and serve as a template for the hole location.
5. Steel structures in corrosive target hall environments are sensitive to paint quality and preparation. For long term exposure in radioactive environments, LORD Aeroglaze® A276 primer

and topcoat has shown to be extremely resilient. For less demanding applications in beamline enclosures, a primer coat and topcoat of Rust-Oleum paint/primer or equivalent has shown to be sufficient.

6. Avoid placement of unpainted steel or rough cut Unistrut on concrete floors, especially in areas with a history of flooding.
7. Structural elements that support alignment devices or adjustment must be many times overbuilt relative to typical stress limits for material. Deformation limits and efforts to reduce deformation during adjustment should be a defined requirement. Horn module support carriages and many beamline support elements in target facilities are overbuilt for the purposes of resisting the vibratory impulse from horn pulsing and / or alignment rigidity.

7.2 Remote Handling

For high radiation areas, consider full lifecycle access and servicing needs and how best to meet them with design, for example repair of foreseeable failures.

Movable structures and stands designed to be used in high radiation areas such as target hall facilities must allow for the use of remote handling lifting fixtures that require no human interaction other than attaching the lifting fixture to a crane. Examples of such structures are the T-blocks and horn/target support modules in the NuMI target hall facility. Lifting fixtures/features should be designed to be significantly oversized so that features and geometrical interfaces are both easily visible and have significant clearance. Sizing and clearances are often driven by the need to be able to view and complete the work by remote camera, as close-up hands-on work with “standard” lifting fixtures is either not possible or very difficult when working through cameras and with a crane hook 50 foot lower than the bridge with a noticeable lag time from operator control movement to hook saddle movement. The clearances are needed to ensure no binding occurs during a move, as a bound fixture presents a major radiological challenge to the labs ALARA principles and in some instances may not be unbound by a person if the dose rates are too high.

Lifting features on remote handled equipment (that interface with the lifting fixture) should be painted different colors to help add depth when working through a remote camera system.

8.0 Appendices

These supplemental files can be found in this ED0011268 item.

8.1 "Appendix 8.1 - FESHM 5100/IBC Load Combination Method and Example.pptx"

This file contains a thorough treatment of load cases, recommendations and examples.

The motivation for this appendix is to guide engineers not familiar with IBC through its requirements, and to encourage consistent interpretation of those requirements.

8.2 "Appendix 8.2 – FESS K. Hartsfield Seismic Loading Interpretation"

The FESS interpretation of IBC/ASCE-7 seismic requirements for non-building structures are outlined in this file.