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Substations – Volume IX – Structures

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Substation Design
Volume IX
Substation Structures

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This series of courses are based on the “Design Guide for Rural Substations”, published by the Rural Utilities Service of the United States Department of Agriculture, RUS Bulletin 1724E-300, June 2001.

Preface

This course is one of a series of thirteen courses on the design of electrical substations. The courses do not necessarily have to be taken in order and, for the most part, are stand-alone courses. The following is a brief description of each course.

Volume I, Design Parameters. Covers the general design considerations, documents and drawings related to designing a substation.

Volume II, Physical Layout. Covers the layout considerations, bus configurations, and electrical clearances.

Volume III, Conductors and Bus Design. Covers bare conductors, rigid and strain bus design.

Volume IV, Power Transformers. Covers the application and relevant specifications related to power transformers and mobile transformers.

Volume V, Circuit Interrupting Devices. Covers the specifications and application of power circuit breakers, metal-clad switchgear and electronic reclosers.

Volume VI, Voltage Regulators and Capacitors. Covers the general operation and specification of voltage regulators and capacitors.

Volume VII, Other Major Equipment. Covers switch, arrestor, and instrument transformer specification and application.

Volume VIII, Site and Foundation Design. Covers general issues related to site design, foundation design and control house design.

Volume IX, Substation Structures. Covers the design of bus support structures and connectors.

Volume X, Grounding. Covers the design of the ground grid for safety and proper operation.

Volume XI, Protective Relaying. Covers relay types, schemes, and instrumentation.

Volume XII, Auxiliary Systems. Covers AC & DC systems, automation, and communications.

Volume XIII, Insulated Cable and Raceways. Covers the specifications and application of electrical cable.

Chapter 1
Structural Issues

Prior to the start of structure design, several factors should be evaluated that may affect the choice of material and member type selected for the structure. Factors influencing selection of material and member type include first cost, cost of erection, deflection characteristics, cost of maintenance, availability, resistance to corrosion and other deterioration, freedom from fire hazard, appearance, size of revenue-producing load served, and temporary or permanent nature of structure.

The American Society of Civil Engineers (ASCE) is a good resource for substation structural design issues including various structure types, loading criteria, deflection criteria, methods of structure analysis and design, and structure connection to foundations.

This course presents concepts about structural design of substations. It does not necessarily reflect the latest standards of practice for structural design. For more information consult the ASCE Methods of Practice (MOP) 113.

Materials

There are four basic materials used for substation structures:

- Steel
- Aluminum
- Concrete
- Wood

Steel is used for most substation structures. Its availability and good structural characteristics generally make it economically attractive. Steel, however, has to have adequate protection from the elements to prevent corrosion. Galvanizing and painting are two widely used finishes for steel substation structures. Because of the protective finish, steel substation structures should not be designed for field welding or field drilling for connections. Field welding is generally uneconomical and usually requires close control over the welding conditions.

ASTM A36 steel is the standard grade of steel used for most rolled-shape members in structural design. Member stresses are usually low, and weight saving is of little advantage. However, should large loads be encountered, coupled with the need for weight reduction, a high-strength steel should be considered such as for line support structures. Structural steel pipe and square tube sections are normally constructed of ASTM A53 Grade B and ASTM A501 steel, respectively.

Aluminum is sometimes used for substation structures where good corrosion-resistant properties are desired. It is about one-third the weight of steel. If aluminum is used, member types should be selected taking advantage of the optimum structural qualities of aluminum and avoiding the shapes in which aluminum members may be a problem. Deflection and torsion has to be carefully reviewed when selecting member types in aluminum. Aluminum has a lower modulus of elasticity and modulus of elasticity in shear than steel; these properties are directly related to deflection and torsional rotation. See Table 1.

Table 1

Comparison of Aluminum vs. Steel Properties

Property	Aluminum	Steel
Modulus of Elasticity	10×10^6	29×10^6
Modulus of Elasticity - Shear	3.8×10^6	12×10^6

Structures designed for aluminum are constructed of Alloy 6061-T6 and should be designed, fabricated, and erected in accordance with the Aluminum Association's Specifications for Aluminum Structures.

Precast, prestressed concrete substation structures may be economical in coastal areas with high winds and a corrosive environment, and also when substations are located near the fabricator's plant. Special considerations are required for the foundation, erection, handling, and equipment mounting characteristics of the structure.

Wood may be used for substation structures. Members have to be treated with an appropriate preservative. Wood poles and members are usually readily available. Structural properties and size tolerances of wood are somewhat variable, and design considerations should take this into account. The life of a wood structure is shorter than for steel, aluminum, or concrete, and maintenance costs may be higher.

Economics is an important consideration when making a material and member type selection. The total cost over the life of the structure should be considered. This also includes the cost of fabrication and shipping, ease of erection, and cost of maintenance.

Functional Structure Types

There are essentially three types of substation structures as categorized from a structural design approach related to the function served in the substation.

Line Support Structures are used as line exit structures, internal strain bus structures, and line terminating structures. They consist basically of two high towers and a crossarm on which the line conductors are attached. They may be used as single-bay or multibay structures.

The major forces acting on these structures are the shield wire and conductor tensions and wind forces. Because of their large size and the magnitude of forces acting on them, these structures are usually highly stressed and require the most design effort.

Equipment Support Structures are commonly referred to as bus support structures, switch stands, lightning arrester stands, line trap supports, etc. In low-profile substation design, these structures are designed primarily as vertical cantilever beams with wind and short-circuit forces being the primary design forces. Deflection may control the design size of some structures and should be reviewed in all structures. Switch stands should be designed to be more rigid than bus supports or other structures because of the dynamic loading effect of the switch blade operation and the requirement that the switch blade has to always return (close) to the relatively small space of the saddle. Any appreciable twisting or deflection of the switch stand may prohibit this function.

Distribution Substation Structure is the column and beam structure, similar to a building frame. It may consist of one or several bays in length and usually is one bay wide. It may vary in height from 20 to 40 feet or more. The structure supports switches and other equipment. It usually will have line conductors attached to one or more sides. This structure should be designed for rigidity and flexibility in equipment location. Generally these structures are composed of box truss members.

Structure Member Types

Three types of structure profile configurations are common in substations today. They are classified from their general physical appearance and structural member components. The types are:

1. Lattice
2. Solid profile
3. Semi-solid profile

1. Lattice Structure

The *lattice structure* consists primarily of angle members forming the chords and lacing of a box truss acting as a beam or column. Depending on the function of the structure (i.e., bus support stand vs. line support structure), the design of the members may or may not be time-consuming and complex.

The lattice structure has been widely used for substation structures for many years. Its box truss beams and columns allow for an efficient use of material. Usually the lattice structure results in the least structure weight compared to other line support structures. It is also very stable and rigid. It is very easy to fabricate, galvanize, and ship. It requires a large amount of bolting and erection time in the field, unless the members are shipped preassembled, and maintenance painting, if required, is costly. Lattice structures are also aesthetically displeasing.

2. Solid-Profile Structure

The *solid-profile structure* is made from wide flange shapes, pipes, tapered round or polygonal shapes, and rectangular tube shapes. The aesthetic appearance, relatively short erection time, and ease of maintenance make the solid-profile structure a popular choice for equipment support structures. The weight penalty on solid-profile equipment support structures is smaller than on line support structures.

The square tube has good torsional resistance and is equal structurally about either major axis. The wide flange shape has a minor axis that may control the design. It has an open cross section and minimal resistance to torsional loads. Wide flange shapes are more suitable for bolted structural connections and may require less welding during fabrication.

Line support structures may be made of straight or tapered tubular round or polygonal poles. The tower may be either an A-frame configuration or a single pole. Wide flange shapes may be used in the A-frame tower. Crossarms are made of straight or tapered round or polygonal members. A combined section from wide flange shapes is used for crossarms also. Tapered poles may have telescoping or flanged splice connections when the pole is galvanized. Painted poles may have welded splice joints and are hermetically sealed to prevent oxidation inside the pole.

Tapered poles are almost always designed by the pole fabricator to the loading requirements specified by the engineer.

3. Semi-Solid Profile Structure

The third structure type is *semi-solid profile*. This type of structure is made from wide flanges and pipes or tubes that form the major members, and is braced between these major members with angle bracing. The design of this structure type is similar to the lattice structure and is very stable and rigid because of the bracing.

Each of the structure member types has its advantages and disadvantages, both from an economical and design viewpoint. Lattice structures are usually economically comparable in aluminum and steel. The basic design approach is also the same. Solid-profile structures used for equipment support structures in aluminum may be as economical as steel in favorable geographical locations. Design effort for aluminum members used in equipment support structures requires more time because of buckling characteristics and weld effect on allowable stresses. However, the desirability of aluminum's good weathering characteristics and light weight are positive factors that have to also be evaluated.

Design

Design loads for substation structures should be categorized as either line support structures or equipment support structures.

Line Support Structures

The design loading criteria for line support structures should be very similar to the criteria for a transmission line tower. The maximum loading condition and line tension are usually furnished by the transmission engineer. For strain bus structures the substation engineer should base the design upon those design loads that will be a maximum for the various components of the structure.

A more positive determination of the structure capacity can be made if an overload is applied to the forces and the structure members are designed utilizing yield stresses. The information is also beneficial for future line changes for substation upgrading or other electrical load modifications.

The components of this structure should be able to withstand the stresses induced by the most critical loading (multiplied by an appropriate overload factor) affecting the component member. These loadings are listed here for overload factor correlation. Overload factors for metal and pre-stressed concrete structures are as follows:

NESC (Heavy, Medium, Light)

Wire Pull	1.65
Wind	2.50
Vertical	1.50

High Winds @ 15°C

Wire Pull	1.3
Wind	1.3
Vertical	1.3

Heavy Ice @ –1°C

Wire Pull	1.3
Vertical	1.3

Other Wind & Ice Combination

Wire Pull	1.3
Wind	1.3
Vertical	1.3

Seismic Loading

All Masses	1.3

The line support structure is designed for two line angle conditions:

1. All wires perpendicular to the crossarm, and
2. The angle of all wires deviating from perpendicular to the crossarm at 15 degrees.

Local conditions may require a larger angular deviation. In addition to the stresses, the engineer should also consider deflection limitations for line support structures. Unless particular circumstances dictate otherwise, the limitations listed may be used as guidelines:

Crossarms
Δh =< 1 to 1-1/2% of span for maximum tension with overload factor
Poles (at top)
Δh =< 4 to 5% of height for maximum tension with overload factor

Lattice towers and solid-profile A-frame towers usually present no problems with deflection. The single-pole-type line support structure has to be carefully reviewed for deflection limitations, particularly if it is acting as a line deadend structure and also is supporting backspan conductors.

Single tubular poles often are used for tall lightning masts. Damping devices should be used to reduce or negate vibrational forces created by the wind blowing at or near the natural frequency of the pole. One such device may be fairly heavy steel chain, encased in a fire hose (to protect the pole finish) and suspended from the top of the pole on the inside of the pole.

Equipment Support Structures

Equipment support structures should be designed for all applicable wind, ice, short-circuit, and dead and dynamic operating loads of equipment. Steel substation structures generally should conform to the requirements of NEMA Publication SG-6.

Ice loading is usually not the controlling design load for equipment support structures but should be reviewed. Wind loads plus short-circuit forces usually produce the maximum stresses in the structures.

Although not normally a critical factor on bus supports and other stationary type equipment stands, deflection limitations are important for switch stands. Follow deflection limitations as specified in NEMA Publication SG 6 unless special conditions dictate otherwise.

Bus support structures and other stationary equipment stands should be designed for a reasonable amount of rigidity. Members stressed to near their allowable stresses may result in structures that perform unsatisfactorily.

Basically, the wind load is assumed for design purposes to be a statically applied load. In reality, it fluctuates in magnitude, and oscillating motion may be induced in the structures. This motion is most unpredictable but can be somewhat alleviated by selecting members that may be larger than required by the calculations and will provide reasonable rigidity for unknown effects. Allowable working stress design values should be used for equipment support structures.

Equipment support structures consisting of solid-profile members may be designed either with the base plate in full contact with the foundation or resting on leveling nuts slightly above the foundation. The design with the leveling nuts has several advantages:

- It eliminates need for close tolerance work on foundation elevation and trueness of surface.
- It allows for some flexibility for structure alignment as a result of fabrication tolerances and buswork fit up.
- The base plate is not resting in any standing water on the foundation.

Anchor bolt sizes may be required to be slightly larger because of additional bending stress induced. The space between the bottom of the leveling nut and the nominal top of the foundation is usually ½ inch.

Designing structures for seismic loading can be a very involved, time-consuming procedure involving dynamic analysis and response spectra. In certain areas of high seismic risk or when sensitive equipment is to be installed, such analysis may be necessary. For most design purposes, more simplified methods can be used, such as those found in the ASCE Substation Design Guide.

Seismic or earthquake loads are environmental loads that are governed by the region of the country in which they occur. In substation design, seismic loads are not usually combined with ice and wind loads, but may be combined with short-circuit forces or operating loads if these loads can occur as a result of seismic activity.

The United States is broken into six seismic regions as shown in Figure 1, UBC Seismic Zone Map of the United States.

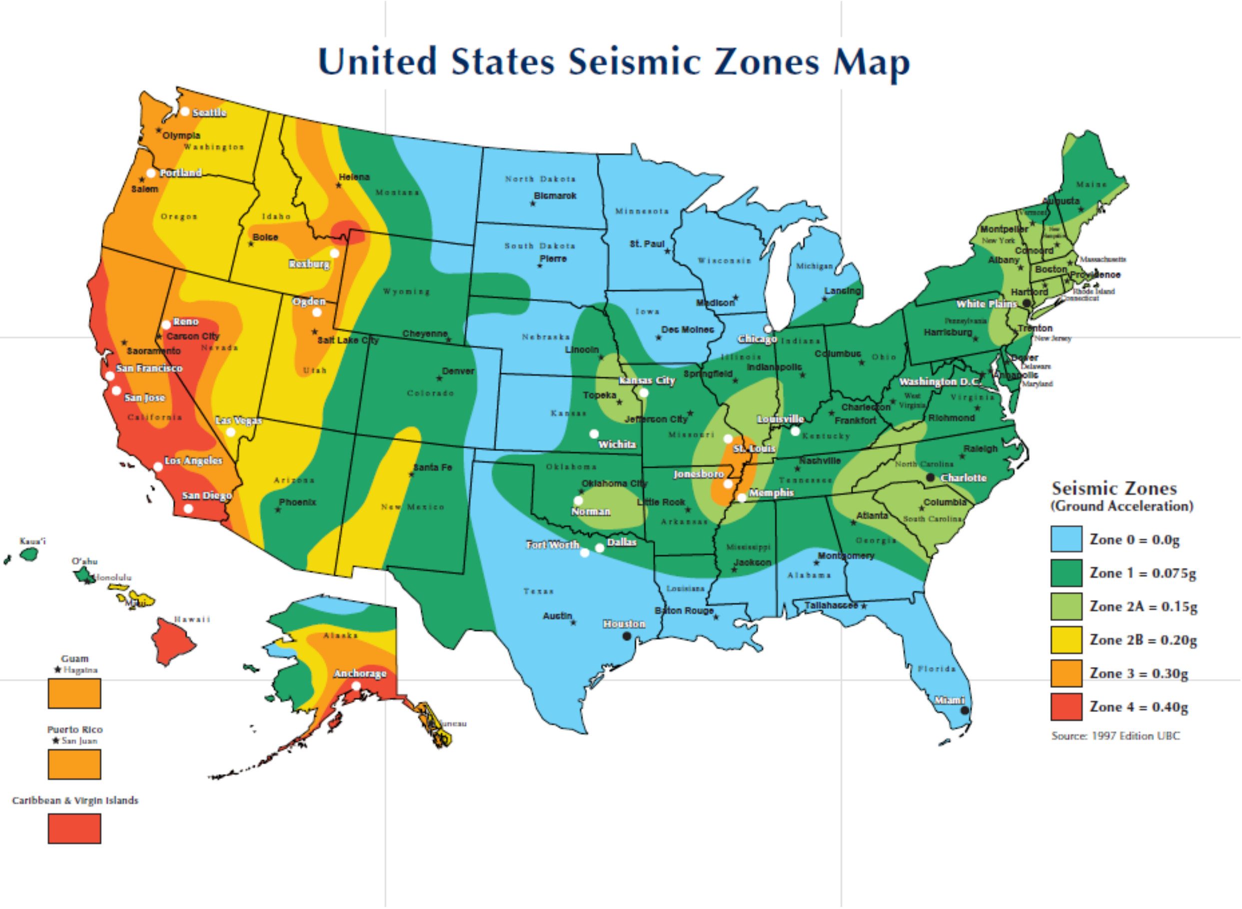


Figure 1

A zone factor, “Z”, ranging from 0.0 to 0.4g is determined based on the site location. The zone factor is equivalent to the *zero period acceleration* (ZPA) of the ground motion. Values of “Z” are indicated in Table 2.

Table 2
UBC Seismic Zone Factors

Zone	**0**	**1**	**2A**	**2B**	**3**	**4**
Z	0	0.075	0.15	0.20	0.30	0.40

Substation structures are divided into four types when considering seismic loading criteria:

- ST1 Single- or Multi-Bay Rack (Not supporting equipment)
- ST2 Single- or Multi-Bay Rack (Supports equipment and/or conductors)
- ST3 Rigid Isolated Support (Supports equipment)
- ST4 Flexible Isolated Support (Supports equipment)

Rigid and flexible isolated supports (ST3 and ST4) in voltage classes greater than 121 kV, and within Seismic Zones 3 and 4, should be designed and qualified according to IEEE Std. 693, “Recommended Practices for Seismic Design of Substations.” For these structures, the procedure below can be used as a check against wind and ice load cases to determine controlling load cases, but IEEE Std. 693 should be used for final design.

The design procedure described below can be used for the design of:

- Rigid isolated supports and flexible isolated supports (Types 3 and ST4) in Seismic Zones 1, 2A, and 2B.
- Rigid isolated supports and flexible isolated supports (Types 3 and ST4) for equipment in voltage classes 121 kV and below in Seismic Zones 3 and 4.
- Racks (single- or multi-bay) and A-frames (Types ST1 and ST2) in all Seismic Zones.

The design base shear is determined using these equations,

$$\mathbf{V = \frac{ZIC}{R_w} * W}$$

$$\mathbf{C = \frac{1.25 * S}{T^{\frac{2}{3}}}}$$

Where:
V = Total design lateral force or shear at the base
Z = UBC Seismic Zone Factor

R_w = Structure Type Factor
C = Numerical Coefficient (C =< 2.75)
S = Site Coefficient for Soil Characteristic, see Table 3.
T = Fundamental Period of Vibration, in seconds
I = Importance Factor
W = Seismic Dead Load (including all rigidly attached equipment or conductor; flexible attachments, such as conductor, need not be included)

Table 3

Coefficients for Soil Characteristics

Description	S Factor
Rock-Like material, shear wave velocity greater than 2,500 fps or Medium-dense to dense or medium-stiff soil conditions, depth less than 200 feet	1.0
Predominately medium-dense or medium-stiff to stiff soil conditions, depth exceeds 200 feet	1.2
Soil profile containing more than 300 feet of soft to medium-stiff clay but not more than 40 feet of soft clay	1.5
Soil profile containing more than 40 feet of soft clay, shear wave velocity less than 500 fps	2.0

The *Importance Factor*, I, may be,

- 1.0 - Based on UBC Life Safety
- 1.25 - Based on UBC Life Safety and functional performance after a seismic event
- 1.5 - Same basis as 1.25 but for anchorage systems depending on the importance of the structure to the electric system.

The *numerical coefficient*, C, may be assumed to be 2.75 if the soil conditions are unknown, regardless of the soil type or period.

The *Structure Type Factor*, R_w, is based on the lateral force resisting system of the structure. Substation structures can be generally classified as shown in Table 4.

Table 4

Type Factor for Structures

Structure Type	Rw
Moment-Resisting Steel Frame	6
Trussed Towers	4
Raised Tanks or Inverted Pendulum	3

Conservatively, it is recommended that a value of $R_w = 4$ be used for most rack-type structures (Types ST-1 and ST-2). Structures such as an isolated bus support (freestanding inverted-pendulum) could use a value of three.

Wind Loads

Several methods of determining wind loads are used. One widely used method is found in NEMA Std. SG6. Wind pressures on flat surfaces are obtained using,

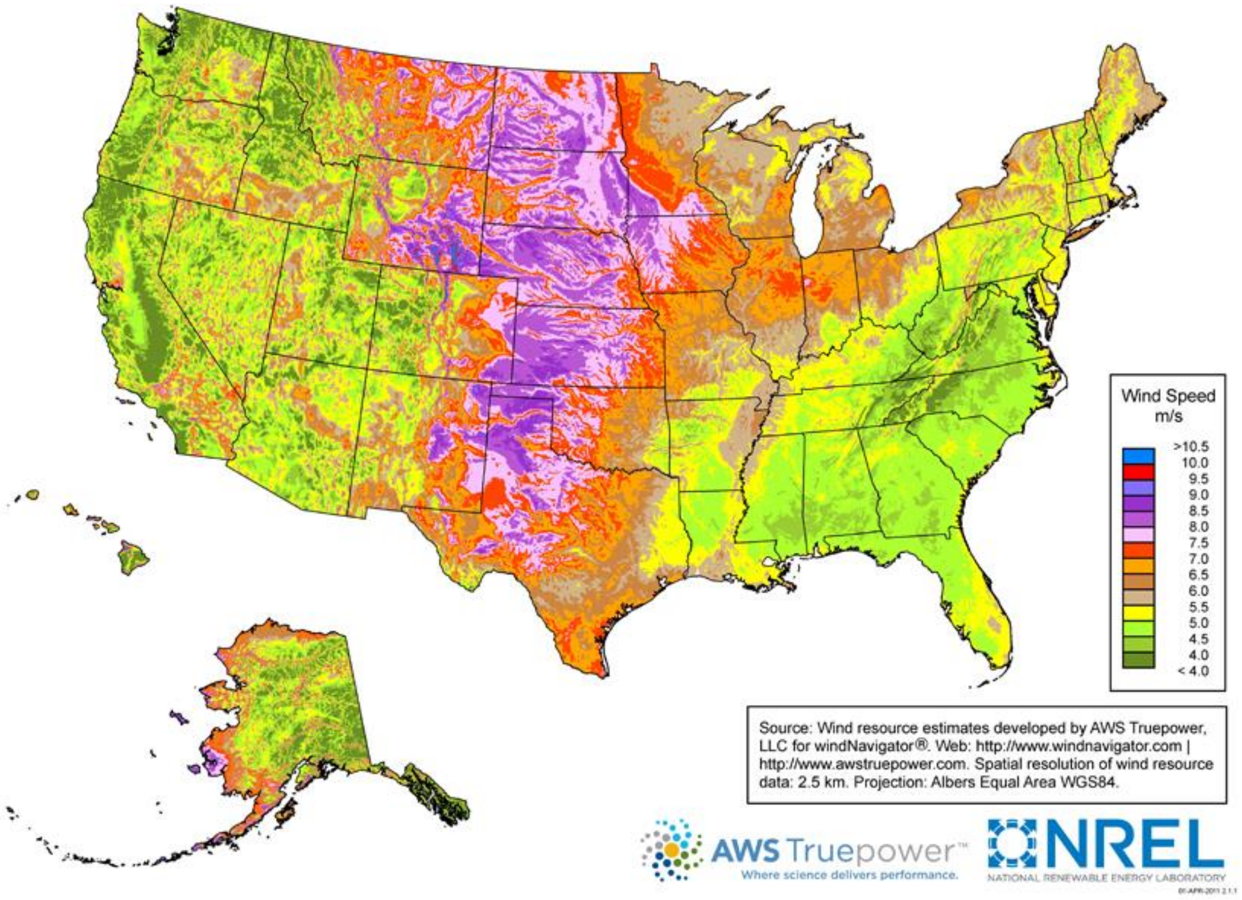
$$\mathbf{P_w = 0.0042 * V^2}$$

Wind pressures on cylindrical surfaces are obtained using,

$$\mathbf{P_w = 0.0026 * V^2}$$

Where:
P_w = Pressure on the projected area, psf
V = Design wind velocity, mph

The design wind velocity for a given area is determined from the probable wind velocity over the design life of the structure, say a 50-year period of recurrence. This information can be obtained from a wind map such as shown in Figure 2 or may be derived from local climatological data.



Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

Figure 2

For wind loading on lattice structures, the projected area used is one and one-half times the area of exposed members. The approach in this course is based on ANSI/ASCE Std. 7-95, "Minimum Design Loads for Buildings and Other Structures." Under this approach, the "3-second gust" wind speed at a height of 33 feet is used as the basic wind speed for design. The basic wind speed to be used can be obtained from Figure 2. The wind load on a structure can be determined using,

$$\mathbf{P_w = C * C_D * K_Z * G_F * V^2 * I}$$

Where:
P_W = Wind pressure lb/ft^2
$C = 2.56 \times 10^{-3}$
CD = Drag coefficient
K_Z = Height and exposure factor
GF = Gust factor
V = Basic wind speed at 33 feet above ground, mi/hr

I = Importance factor

Each of the above variables is discussed below.

Constant, C. This is a constant that yields a value for F_W.

Drag coefficient, C_D. The wind load on a conductor or a structure varies with its shape. The drag coefficient reflects that variation. The coefficient can vary between 1.0 for round, smooth shapes to about 2.0 for flat surfaces.

Height and exposure factor, K_Z. In the height range from zero feet to 30 feet and for exposure categories A, B, and C, the height and exposure factor $K_Z = 1.0$. For exposure category D, $K_Z = 1.16$. The exposure categories are explained below:

Exposure A: Large cities' centers with at least 50 percent of the structures having a height greater than 70 feet.

Exposure B: Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger.

Exposure C: Open terrain with scattered obstructions having heights generally less than 30 feet. Open country and grassland is included in this category.

Exposure D: Flat, unobstructed areas exposed to wind flowing over open water for a distance of at least 1 mile.

Gust factor, G_F. A gust factor of 0.8 should be used for exposure categories A and B, and 0.85 should be used for exposure categories C and D.

Importance factor, I. An importance factor of 1.15 should be used for electric substations.

Consideration should also be given to construction loads that can be periodically imposed on structures such as pulling and hoisting equipment into place. While such conditions do not usually govern design, they should be evaluated.

Loading Combination for Design

In addition to designing equipment stands for the extreme loads, bus supports are also designed for a combination load of extreme wind and short-circuit loads. The load combination design should be limited to calculations of stress and should not consider deflection of the structure.

Typical Design Approach

There are basically two approaches to design of steel structures: *Allowable Stress Design* (ASD) and *Load and Resistance Factor Design* (LRFD).

The ASD approach is defined by the American Institute of Steel Construction's (AISC) Manual of Steel Construction, ASD. In the ASD, the stresses induced by various service loads (wind, ice, etc.) in a selected member are compared to allowable stresses established in the AISC manual.

In LRFD, load factors are applied to the service loads, or loads the structure is actually expected to see. Then a member is selected that will have sufficient strength to resist the factored loads. In addition, the theoretical member strength is reduced by an applied resistance factor. The selection of the member has to satisfy the following:

Factored load < Factored strength

The *factored load* is the sum of all the working loads to be resisted by the member. Each load is multiplied by its own load factor. Dead loads, for example, will have load factors that are different from live load factors. The *factored strength* is the theoretical strength multiplied by a resistance factor. Load and Resistance Factor Design of steel structures is very much similar to the approach to reinforced concrete design used for several years in the American Concrete Institute's Building Code where it is known as *strength design*.

The benefit of ASD is that it is straightforward and familiar to most structural engineers. With the LRFD approach, load factors model the likelihood, or probability of certainty, of various types of loads. For example, dead loads can typically be determined with more certainty than can live loads. Therefore, the load factor for a dead load is less than that for a live load.

The resistance factors applied to the member's theoretical strength account for uncertainties in material properties, design theory, and fabrication and construction practices. One might say that the LRFD is a more realistic approach to structure design. The guidelines and specifications for LRFD are published in AISC's Manual of Steel Construction, Load Factor & Resistance Factor Design.

Chapter 2
Design Examples

This chapter includes several basic design examples. Several examples are illustrated depicting the design of the main member for a single-phase bus support. These examples show a typical approach for the design of most equipment support structures using allowable stress design. The examples include a square tube and a lattice column, all composed of steel.

Lighter weight members may still meet the loading and deflection criteria. However, smaller size members may present fabrication problems in the lattice structure. In general, for voltages up to 230 kV, structures using tubular members are as economical as lattice or wide flange structures when weight, ease of fabrication, and ease of erection are considered.

The following is an example of a design for a single-phase bus support for a substation in Lansing, Michigan, given the following information (See Figure 3):

- Height of bus centerline above foundation, 18 feet
- Schedule 40 aluminum bus, 3.5 inch (weight = 3.7 lbs/ft)
- Maximum short-circuit force, 38.5 lbs/ft
- Short-circuit reduction factor, 0.66
- Bus support spacing, 19.7 feet
- Insulator, 6.5 feet high, 11-inch diameter, and 310 lbs
- Weight of Structural member, 19.4 lbs/ft

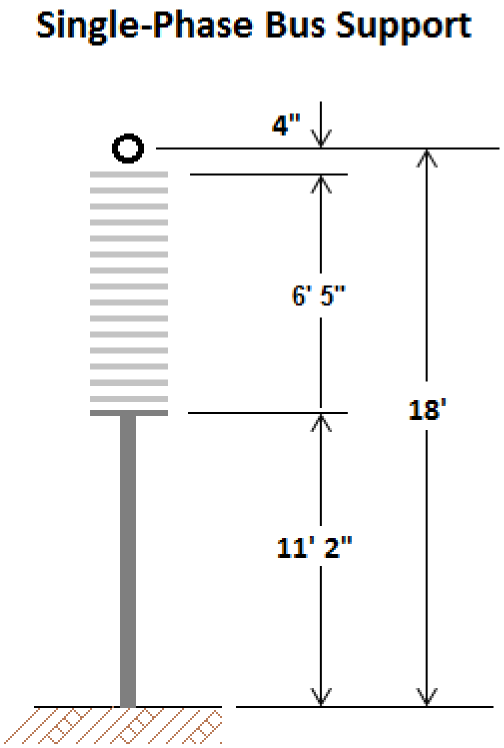


Figure 3

First Case: Design a tubular structure, A500 or A501 steel

Short-Circuit Loading

The short circuit loading is found by multiplying the bus support spacing (19.7 feet) by the maximum short circuit force (given as 38.5 lbs/ft) times a short circuit reduction factor (0.66).

$F_{sc} = 19.7' * 0.66 * 38.5$ lbs/ft = 500 lbf

With a structure height of 18 feet this results in an overturning moment of,

Mom @ base = 18' * 500 lbf = 9,000 ft-lbs.

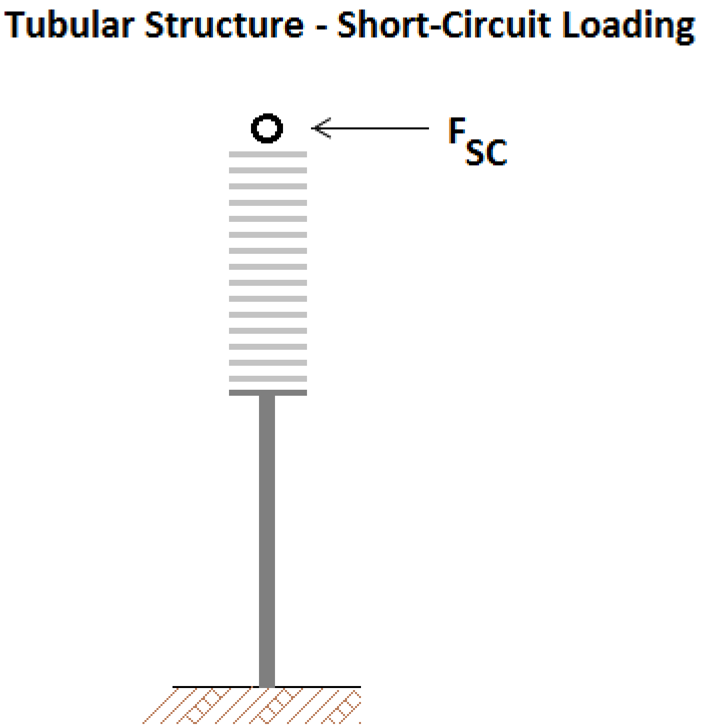


Figure 4

Wind Loading

The wind loading is based on the extreme 50-year wind of 70 mph.

Extreme 50-year wind, 70 mph. See Figure 4.

For flat surfaces (e.g., the structural support),

$P_w = 0.0042 * 70^2$

$P_w = 20.58 \text{ lbs/ft}^2$

For cylindrical surfaces (e.g., the bus and insulator),

$P_w = 0.0026 * 70^2$

$P_w = 12.75 \text{ lbs/ft}^2$

The following tabulation shows the calculations for the wind on the bus, insulator, and structure.

Description	**Force**	**Moment Arm**	**Moment @ Base**
1. Wind on Bus	19.7’ * 12.74 * 0.33 ft^2/ft = 83 lbf	18’	1,494 ft-lbs
2. Wind on Insulator	6.5’ * 12.74 * 0.92 ft^2/ft = 76 lbs	14.4’	1,094 ft-lbs
3. Wind on Structure (assume 3.06 in^2)	11.2’ * 20.58 * 0.66 ft^2/ft = 151 lbf	5.6’	846 ft-lbs
Totals	310 lbf		3,434 ft-lbs

Therefore, the total wind load on the structure is 310 pounds and produces an overturning moment of 3,434 ft-lbs.

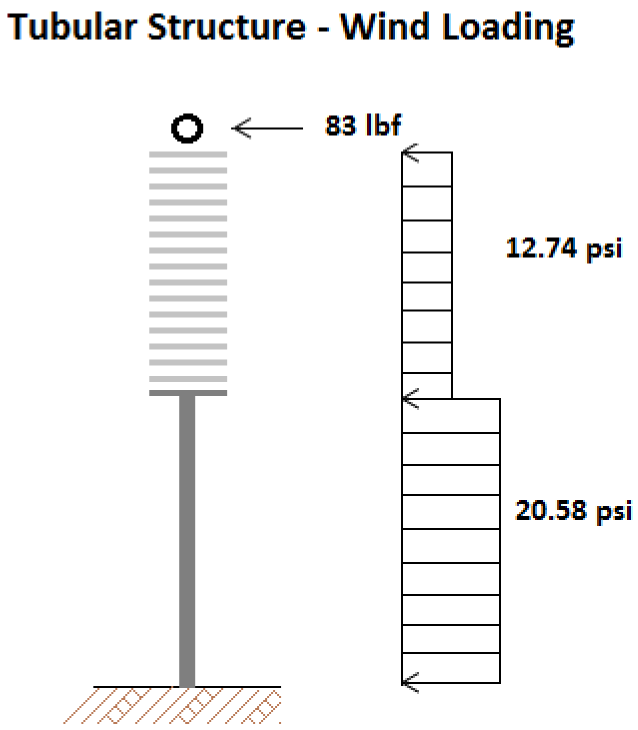


Figure 5

Heavy Ice Loading

Assume:

Ice = 1”

Ice Density = 57 lbs/ft^3

Structure Weight = 19.4 lbs/ft

Adding the 1” of ice to the 4” (0.33’) bus results in a 6” (0.50’) diameter of iced bus. The bus weight of the bus is 3.7 lbs/ft. The insulator diameter is 0.92’ and adding the ice results in an overall diameter of 1.09’. The insulator weighs 310 pounds. Therefore,

Description		Load
1. Ice on Bus	$(0.5^2 - 0.33^2) * \pi/4 * 57$ lbs/ft^3	6.31 lbs/ft
1a. Ice & Bus	6.31 lbs/ft + 3.7 lbs/ft	10.00 lbs/ft
2. Ice on Insulator	$(1.09^2 - 0.92^2) * \pi/4 * 57$ lbs/ft^3	15.29 lbs/ft
2a. Ice & Insulator	(15.29 lbs/ft * 6.5) + 310	409 lbs

Once the load data is obtained, these values are then compared to the yield strength of the tubular structure and calculations are performed to insure the structure is not at risk of buckling. These calculations are beyond the scope of this course, but in this case, the structure is not at risk of buckling and the yield structure of the structure is much greater than the load.

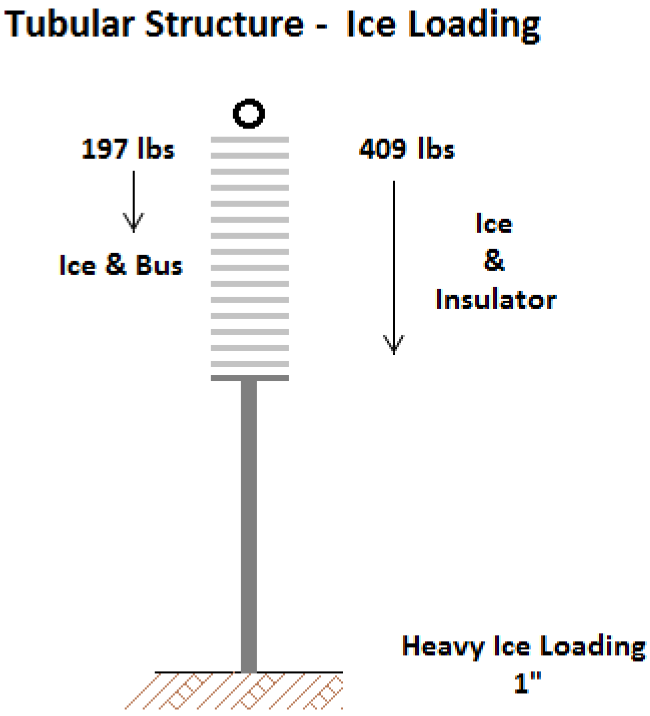


Figure 6

Seismic Loading

Next, we check the seismic loading on the structure. First the shear at the base of the structure is found using,

$$\mathbf{V = \frac{Z*I*C}{R_W} * W}$$

Where,
Z = 0.075, Table 2, Zone 1
I = 1.15 for substations
C = 2.75 (assumed constant)
Rw = 3, Table 4

$$V = \frac{0.075*1.15*2.75}{3} * W$$

V = 0.08W

Applying this factor to the loads on the structure we have moments as shown in the following table.

Description	Force	Moment Arm	Moment at Base
Seismic on Bus	19.7’ * 3.7 lbs/ft * 0.08	18’	105 ft-lbs
Seismic on Insulator	310 lbs * 0.08	14.4’	356 ft-lbs
Seismic on Structure	11.15’ * 19.4 lbs/ft * 0.08	5.6’	97 ft-lbs
		Totals	558 ft-lbs

The combined loading of wind and short-circuit forces (12,434 ft-lbs) produce the greatest forces and moment at the base design for this condition. Therefore, heavy ice and seismic forces are not critical for this structure. For the cantilever structure, bending and deflection are the principal concerns.

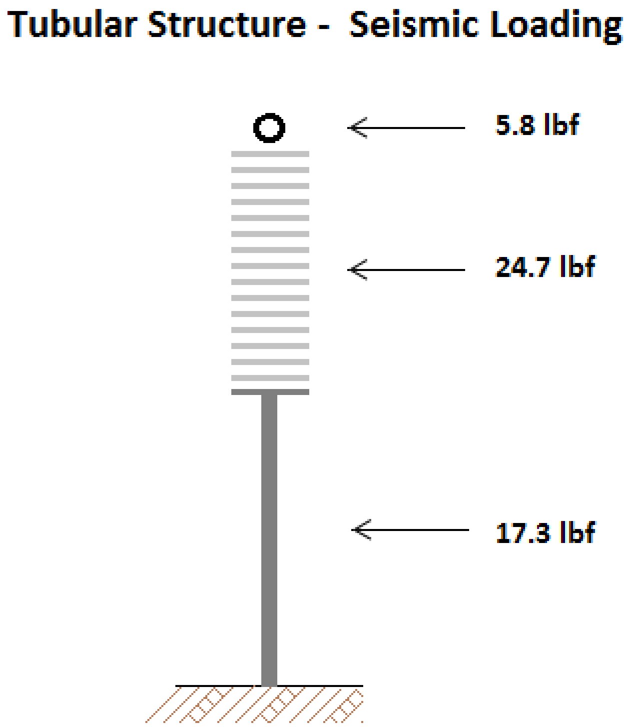


Figure 7

Check Deformation

The next requirement is to check for deformation of the structure and this is based on wind load only. See Figure 8.

Tubular Structure - Deflection Equivalent Loadings

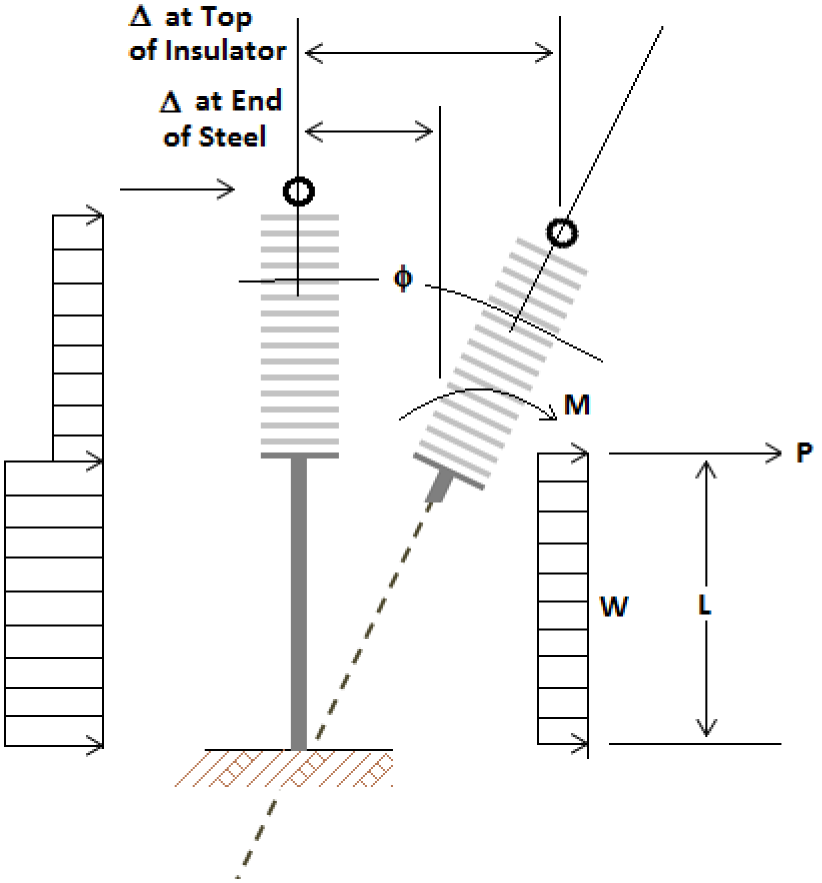


Figure 8

To determine the Deflection Equivalent Loadings the following formulas are used.

$$\Delta \text{ at end of steel} = \Delta_1 + \Delta_2 + \Delta_3$$

Where,

$$\Delta_1 = \frac{P*I^3}{3*E*I}$$

Wind on insulator and bus

$$\Delta_2 = \frac{W*I^4}{8*E*I}$$

Uniform wind on structure

$\Delta_3 = \frac{M * l^2}{2 * E * I}$ Moment at insulator base

The manual calculations are not included, however the results are,

$\Delta = 0.075" + 0.028" + 0.051" = 0.154"$

And for the angle of deflection,

Θ (slope) at end of steel = $\Theta_1 + \Theta_2 + \Theta_3$

$\Theta_1 = \frac{P * l^2}{2 * E * I}$ Wind on insulator and bus

$\Theta_2 = \frac{W * l^3}{6 * E * I}$ Uniform wind on structure

$\Theta_3 = \frac{M * l}{E * I}$ Uniform wind on structure

Again, the manual calculations are not shown but the results are,

$\Theta = 0.00086 \text{ rad} + 0.00027 \text{ rad} + 0.00079 = 0.00192 \text{ rad}$

$0.00192 \text{ rad} * 57.32 = 0.11 \text{ degrees}$

Δ at top of insulator = 0.154" + 78" * sin(0.11)

Δ at top of insulator = 0.30 inches

$$\frac{0.30}{(18' * 12)} = \frac{1}{720} < \frac{1}{200}$$

Acceptable criteria for bus support structure deflections may be taken as 1/200 of the bus height. The analysis shows that for the given conditions the structure is acceptable.

Second Case: Design a lattice structure, A36 steel

For this example, we will assume,

- A box truss 15” square
- Chord angles = 2.5 inch
- Lacing angle = 1.75 inch

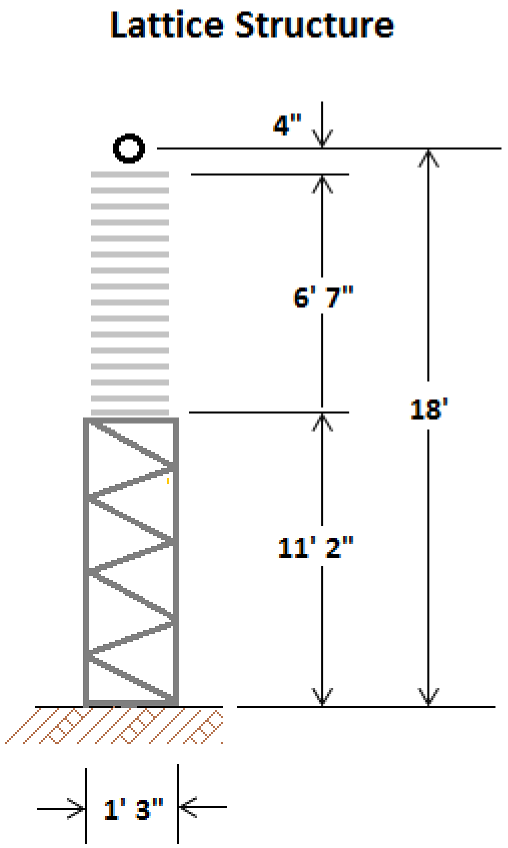


Figure 9

The short circuit calculations are the same for the lattice structure as in the tubular structure and yield the same results.

Wind Loading,

Wind on the insulator was previously calculated to be, 12.74 lbs/ft^2 and the wind on the structure was 20.58 lbs/ft^2. For a lattice structure, the wind on the structure is multiplied by 1.5, for 30.87 lbs/ft^2. The following table shows the results of the wind calculations.

Description	Force	Moment Arm	Moment at Base
Wind on Bus	19.7’ * 12.74 lbs/ft^2 * 0.33	18’	1,491 ft-lbs
Wind on Insulator	6.5’ * 12.74 lbs/ft^2 * 0.92	14.4’	1,097 ft-lbs
Wind on Structure	11.15’ * 30.87 lbs/ft^2 * 0.62	5.6’	1,195 ft-lbs
		Totals	3,783 ft-lbs

The lattice structure has slightly more wind load (3,784 ft-lbs) than the tubular structure (3,434 ft-lbs)

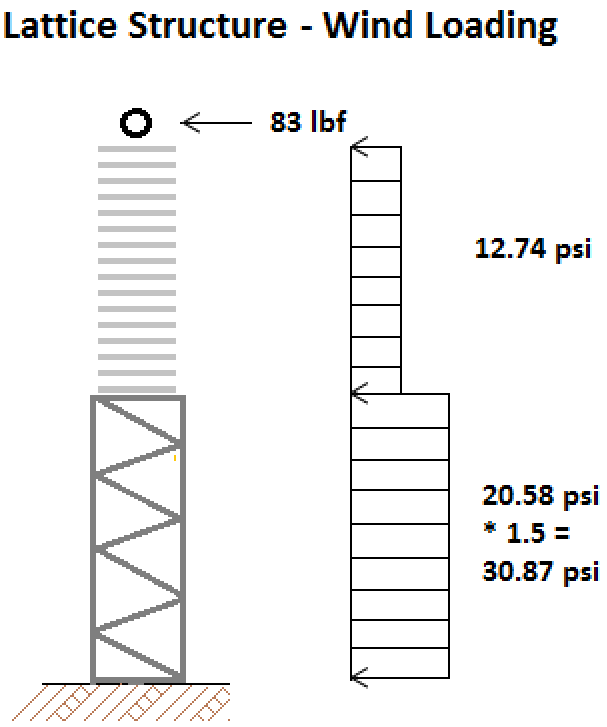


Figure 10

Ice and seismic loads are calculated similarly to the tubular example and in this example will not result in the maximum design loads.

The deflection values for the lattice structure are,

Δ at top of steel = 0.03” + 0.01” + 0.028” = 0.068”

Θ = 0.00030 rad + 0.00010 rad + 0.00028 rad = 0.00068 rad

0.00068 rad = 0.00068 * 57.32 = 0.04 degrees

Δ at top of insulator = 0.068” + 78” * sin(0.04) = 0.12”

$\frac{0.12"}{(18' * 12)} = \frac{1}{1{,}800} < \frac{1}{200}$ So, it’s okay.

Chapter 3
Other Structural Considerations

Three types of structural bolts are typically used in substation structure design. These bolts are designated by ASTM Standard Specifications A394, A307, and A325. For all but the most severely loaded structures, the A394 and A307 bolts will usually be adequate.

If possible, one type of structure bolt and one diameter should be used in any one structure and throughout all the substation structures.

ASTM Standard Specification A394 covers galvanized hex head bolts including hex nuts with sizes from ½ to 1 inch in diameter.

Non-galvanized regular square or hex head bolt and nuts in diameters ranging from ¼ to 4 inches in diameter are covered by ASTM Standard Specification A307. This specification is also used for anchor bolts conforming to the requirements of ASTM A36 structural steel. For substation usage, Grade A bolts are used. Hot-dip galvanizing in accordance with ASTM A153 is required for substation applications.

When high-strength bolts are required, ASTM Standard Specification A325 High Strength Bolts may be used. High-strength bolts are available in sizes from ½ to 1½ inches in diameter. Bolts, nuts, and washers should be galvanized in accordance with ASTM A153, Class C. Nuts should conform to ASTM A563, Grade DH.

Some tabulated bolt values for single shear are given in Table 5. These values may be used for substation structure design when "working stresses" or "yield stresses" are used.

Table 5

Suggested Allowable Bolt Shear

Single Shear on Bolts
Working Stress Design
(KIPS)

ASTM Designation	**Allowable Stress Fv (KSI)**	**Nominal Diameter (inches)**				
		½	**5/8**	**3/4**	**7/8**	**1**
A307	10.0	1.96	3.07	4.42	6.01	7.85

A394	15.0	2.95	4.60	6.63	9.02	11.78
A325	21.0	4.12	6.44	9.28	12.63	16.49

Single Shear on Bolts
Yield Stress Design
(KIPS)

ASTM Designation	**Allowable Stress Fv (KSI)**	**Nominal Diameter (inches)**				
		1/2	**5/8**	**3/4**	**7/8**	**1**
A307	18.0	3.53	5.52	7.95	10.82	14.14
A394	30.	5.89	9.20	13.25	18.04	23.56
A325	36.0	7.07	11.05	15.91	21.64	28.28

Because of the repeated loads, those structures using A307 or A394 bolts should also incorporate either lockwashers or locknuts to prevent loosening of the connections. Standard washers are not normally used with these bolts.

Welding

All welding of structural steel should be in accordance with the latest edition of the Structural Welding Code, D1.l of the American Welding Society. In addition to the required design welds, structures that are to be galvanized should have all joints sealed with a small continuous seal weld. This is to help prevent corrosion or small crevices or cracks between two pieces of abutting steel that the acid bath can penetrate, but not the molten zinc. This is covered in ASTM A385.

Finishes

Galvanized steel has found wide application for substation structures. Hot-dip galvanizing has been the most widely used finish on steel substation structures for the following reasons:

- It is economical (initial cost, touch-up, and general maintenance).
- It provides good resistance to most corrosive environments.
- It has “self-healing” properties against minor abrasions.
- It requires little or no maintenance in most substation applications.

New structures are galvanized in accordance with ASTM Standard Specification A123. Safeguards against embrittlement and warpage and distortion during galvanizing should be in conformance with ASTM Standard Specification A143 and A384, respectively. Galvanized members that are marred in handling or erection or that have had corrective work done should be touched up with a zinc-rich paint. All bolts and steel hardware should be galvanized in accordance with ASTM Standard Specification A153 for Class C material.

When painted structures are desired, there are several systems available. Painting System Specification No. 1.04, SSPC –PS 1.04, from the Steel Structures Painting Council is one paint system that is applicable for galvanized and non-galvanized substation structures. The following is a summary of the system from the seventh edition of the Steel Structures Painting Council's Systems and Specifications manual.

The surface shall be thoroughly cleaned of all oil, grease, dirt, loose mill scale, and other detrimental substances. "Hand tool cleaning" is the minimum surface preparation required for this oil-based system. Depending upon condition of the surface "power tool cleaning" may be necessary. "Solvent cleaning" is only required for new galvanized structures. Specifications for these cleaning systems are outlined in the SSPC manual.

The system calls for a zinc dust–zinc oxide primer that conforms to federal specification TT-P-641G Type 1, which is a linseed oil primer. The second, or intermediate, coat uses SSPC-Paint 104, which is a white or tinted alkyd paint that has good weathering ability and is suitable for exterior exposures. This paint is intended for brush or spray applications and works well as either an intermediate or top coat. There are four types that are color dependent:

Type 1 – white
Type 2 – medium to light gray to tan
Type 3 – light green
Type 4 – dark or forest green

The finish coat should be the same as intermediate coat, but the color has to be specified. This three-coat paint system calls for a minimum paint thickness of 4.5 mils. This consists of a 2.0 mil primer coat, a 1.5 mil intermediate coat, and a 1.0 mil finish coat. The measurements shall be in accordance with SSPC-PA 2, "Measurement of Dry Paint Thickness with Magnetic Gages."

Painted structures should be primed and receive the intermediate coat in the shop. The finish coat may either be applied in the shop or in the field. The finish coat can be applied under ideal conditions in the shop; however, the structure finish may be marred during shipment or erection requiring field touch-up. The SSPC manual gives additional specifications for touch-up painting and maintenance painting as well as providing alternative finish coat systems.

Summary

This course has covered the issues related to designing substation structures. The course has provided the reader with a general overview of the factors and equations used in the design of structures.

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