A Discussion of Power Plant Loads and Load Combinations

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Abstract
This paper focuses on the design of steel support structures within electrical power generating facilities (power plants) which burn fossil fuels to generate electricity. The design of power plant structures requires the determination of loads, some of which will already be familiar to any practicing structural engineer, and some of which are specific to power plant structures. This paper provides guidance to the structural engineer for developing the various loads for power plants, and for combining these loads to determine the overall design loads. The discussion will be based around the use of Minimum Design Loads for Buildings and Other Structures, ASCE 7-10. (Note: where specific text from ASCE 7-10 is quoted or cited in this paper, it is with permission from ASCE.)

Many of the loads involved in the design of power plant structures are the same as those encountered in the design of any typical building or structure, such as dead load, live load, snow load, wind load, and earthquake load. However, for each of these loads there are characteristics which are specific to power plants, and these are discussed in this paper. In addition, the design of a power plant structure involves loads which are not specifically discussed in ASCE 7-10. Examples of these loads include ash load, unbalanced pressure forces, forces due to thermal expansion and contraction of high-temperature equipment and ductwork, and boiler loads. The characteristics of these loads are discussed. The basic allowable strength design (ASD) load combinations found in ASCE 7-10 are expanded to include the additional primary loads specific to power plants. Finally, considerations for developing factored load combinations with power plant loads, for use with load-and-resistance-factor design (LRFD) methods, are discussed.

The First Step: Determine the Risk Category
To apply the ASCE 7-10 provisions for determining flood load, wind load, snow load, ice load and earthquake load, a building or structure must be classified according to Table 1.5-1 in ASCE 7-10. The Risk Category assigned to the building or structure dictates the various importance factors to be used in determining the minimum design environmental loads.

From Table 1.5-1, Risk Category III includes “Buildings and other structures not included in Risk Category IV [essential facilities], with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.” Power generating stations meet this definition and are therefore typically assigned to this Risk Category III. Although they provide power to Risk Category IV facilities such as hospitals, police stations, fire and rescue stations, those facilities typically have their own backup power provisions; for this reason power plants are not usually considered to be Risk Category IV facilities.

Dead Load and Collateral Dead Load of Power Plants
There are certain types of loads which are normally considered dead load, but which should be given special consideration since they may not always be present in the structure. If they are simply added in with the permanent dead load, an unsafe overestimation of the resistance to uplift forces could result. For example, the weight of fixed (permanent) equipment is normally classified as dead load. But the contents of the permanent equipment, such as the water weight in the boiler, weight of the coal in coal silos,
the contents of tanks, etc., will not always be present (during shutdown periods, for example). In power plants, especially in the boilerhouse, this will constitute a large portion of the dead load.

To avoid this potentially large overestimation of the permanent dead load, the engineer can create a separate primary load called “collateral” dead load. When determining the maximum gravity load for designing a particular structural element, this collateral dead load is included in the load combinations, but when designing for minimum gravity load (such as when determining net uplift forces on anchor rods and foundations, for example), this load is neglected.

Sometimes the weight of the contents is included in the “live load” category, but doing so will result in an inconsistency with the philosophy behind the ASCE 7-10 load combinations. Most of these loads are present at their full value during operation of the plant and not truly transient. Thus they should not be reduced to an “arbitrary-point-in-time” value in load combinations, as is live load. This will be further discussed later in this paper.

If the engineer does create the collateral dead load category, there are other loads which should be included. One is the additional uniform load allowance which is typically applied throughout the power plant structure to account for small bore piping, valve stations, electrical conduits/cable trays and other minor items. Applying this load to all beams eliminates the need to redesign individual beams once specific pipe and conduit/cable tray routings are determined. But this can also add significantly to the overall dead load, and since it may not actually be present it should be included with collateral dead load. Another load to include in the collateral dead load category would be any contingency loads which are added to the structural columns, which is a typical practice to account for unanticipated loads and allowance for future equipment.

Live Load for Power Plants

Live load is defined in Chapter 4 of ASCE 7-10 as “…load produced by the use and occupancy of the building or other structure…” Examples of this type of load in power plants include uniform and concentrated loads on floors, platforms and catwalks, roofs, concentrated loads on ladders, linear and concentrated loads on handrails and guardrails, crane loads, and impact loads from operating equipment. Requirements for many of these loads are found in ASCE 7-10, but some, especially the uniform design live loads for the various floors and platforms in power plants, are not specifically defined in ASCE 7-10. According to ASCE 7-10, the live loads which are selected for design shall be the maximum loads expected during the use of the structure. For power plants, the floor and platform live loads need to account for equipment maintenance where appropriate, including considerations for parts laydown during equipment dismantling and portable equipment used during maintenance.

Snow Load and Rain Load on Power Plant Structures

Snow loads and rain loads for power plants can be determined directly from ASCE 7-10. Drift load from the boilerhouse roof must be included when determining snow loads on adjacent structures, such as the turbine area and the ductwork and scrubbers typically found at the back end of the boilerhouse. The roofs of exterior precipitators, scrubbers, and fabric-filter dust collectors will also cause drift load on adjacent ductwork and other structures, which must also be considered.

Wind Load on Power Plant Structures

For most of the structures encountered in power plants, ASCE 7-10 provides all the necessary information to determine the wind loads. Enclosed structures are designed for wind the same as any typical building. Exterior ductwork, precipitators, fabric-filter dust collectors (baghouses), scrubber vessels, stacks, etc., are considered “other structures” for wind load determination, and Chapter 29 of ASCE 7-10 should be used to determine the wind loads on these structures.

Determining the wind load on open structures such as pipe racks, equipment support towers and unenclosed boiler support structures requires special consideration. For these types of structures, the wind load provisions of ASCE 7-10 can be supplemented by the recommendations found in the ASCE publication Wind Loads for Petrochemical and Other Industrial Facilities.

Seismic Design of Power Plant Structures

A detailed discussion on seismic design is beyond the scope of this paper. This section will focus on key issues which will be encountered in power plant seismic design, to assist the engineer in properly applying the seismic provisions found in Chapters 11 through 23 of ASCE 7-10.

Types of structures found in power plants

The seismic design of power plants will typically involve three types of structures: 1) “buildings”, covered by Chapter 12 of ASCE 7-10, 2) “nonstructural components”, covered by Chapter 13, and 3) “nonbuilding structures”, covered by Chapter 15. Nonbuilding structures are further classified into two types: “nonbuilding structures similar to buildings,” and “nonbuilding structures not similar to buildings,” and both types will be found in a typical power plant.

Structures housing the power plant administration facilities should be classified as buildings. Structures such as pipe racks, equipment support towers, boilers, scrubbers, etc., are classified as nonbuilding structures. For some of the structures found in power plants, properly classifying the structure is not as straightforward and
requires judgment. The commentary to Section 11.1.3 of ASCE 7-10 provides guidance. It states: “Many industrial building structures have geometries and/or framing systems that are different from the broader class of occupied structures addressed by Chapter 12, and the limited nature of the occupancy associated with these buildings reduces the hazard associated with their performance in earthquakes. Therefore, when the occupancy is limited primarily to maintenance and monitoring operations, these structures may be designed in accordance with the provisions of Section 15.5 for nonbuilding structures similar to buildings.”

In a power plant, this applies to the boiler support structure, isolated pump houses and similar site enclosures; these can be classified as nonbuilding structures similar to buildings.

Selecting the analytical procedure for power plant structures

The analytical procedure for both buildings and nonbuilding structures similar to buildings is selected according to Section 12.6 of ASCE 7-10. The complexity of the seismic analysis required depends on the characteristics of the structure and the Seismic Design Category. In Seismic Design Category B or C, an equivalent lateral force analysis is permitted for all structures, and is typically used for all power plant structures.

In the higher Seismic Design Categories D, E and F, there are restrictions on the use of the equivalent lateral force method which may apply, depending on the structure height, period and whether certain types of irregularities are present. Refer to Table 12.6-1 in ASCE 7-10. The boiler support structure, for example, supports large masses such as the boiler, coal silos, SCR reactor and air heater, which are distributed irregularly throughout the structure. The boiler itself extends nearly the entire height of the support structure, interrupting the ability to provide full-floor rigid diaphragms. While the entire weight of the boiler is hung from near the top of the structure, earthquake forces are transferred by lateral ties or bumpers between the structure and the boiler at various levels. Thus the boiler support structure typically has both horizontal and vertical irregularities of the type which will not permit the use of the equivalent lateral force method in the higher Seismic Design Categories. When this is the case, a dynamic analysis is required.

Nonbuilding structures supported by other structures

When a nonbuilding structure is supported by another structure, Section 15.3 of ASCE 7-10 applies.

As long as the nonbuilding structure is not part of the primary seismic force-resisting system, the required method of analysis depends on the combined weight condition. If the mass of the nonbuilding structure in question is less than 25% of the total seismic mass of the nonbuilding structure plus the supporting structure (including other nonbuilding structures supported by the same structure), Section 15.3.1 applies. This section requires the seismic forces on the nonbuilding structure to be determined in accordance with Chapter 13 (nonstructural components requirements). If, however, the mass of the nonbuilding structure equals or exceeds 25% of the total seismic mass of the nonbuilding structure plus the supporting structure (including other nonbuilding structures supported by the same structure), Section 15.3.2 applies. This section requires an analysis which combines the structural characteristics of the supported nonbuilding structure and the supporting structure. The specifics of the analysis depend on whether the nonbuilding structure is considered rigid (fundamental period less than 0.06 seconds) or nonrigid (fundamental period equal to or greater than 0.06 seconds). If the nonbuilding structure is rigid, the combined analysis is used to design the supporting structure, but the nonbuilding structure itself and its attachments must be designed for the “component” forces using Chapter 13. If the nonbuilding structure is nonrigid, the combined analysis is used to design both the supporting structure and the nonbuilding structure.

In power plants, many of the nonbuilding structures are supported by other structures, and the provisions of Section 15.3 should be applied. One area of special concern in power plant seismic design is the determination of the forces in the boiler ties and bumpers which transfer lateral forces between the boiler and the boiler support structure. Because the boiler walls are tied to the structure at various levels, the boiler stiffness will interact with the structure stiffness, and there will be a sharing of seismic force resistance between the two. Thus, it is prudent to consider the boiler part of the seismic force-resisting system, and a combined analysis should be performed to determine the boiler tie forces regardless of the combined weight condition.

Nonstructural components in power plants – importance factors

Chapter 13 in ASCE 7-10 covers the seismic design criteria for nonstructural components that are permanently attached to the supporting structure. A component importance factor (Ip) must be assigned to each component in accordance with Section 13.1.3. This component importance factor is not the same as the overall seismic importance factor used for building and nonbuilding structure design, which is dependent on the Risk Category as discussed earlier. The component importance factor is either 1.5 or 1.0, depending on the intended function of the component and/or if it contains hazardous material. Hazardous materials are generally thought of as toxic, flammable or explosive substances, but in power plants there are other considerations which may cause some components to be assigned an Ip value of 1.5. One example would be the piping systems that carry high pressure steam or condensate which would be extremely dangerous if they were to rupture. Consideration should be given to assigning a 1.5 importance factor to these systems, or at least the portions of these systems that are routed near stair towers or walkways required for exiting the facility.
Power Plant Loads Not Specified in ASCE 7

The next several sections of this paper will discuss the various loads which are encountered in the design of power plants but for which no guidance is found in ASCE 7, including ash load, sustained and transient pressure forces, friction forces, and boiler loads.

Classifying power plant loads for inclusion in load combinations

Load combinations which include the additional power plant loads must be consistent with the basic philosophy behind the ASCE 7-10 load combinations. This philosophy, as discussed in Chapter C2 of the commentary therein, is that, except for permanent loads such as dead load, most loads are transient in nature; that is, they vary with time between their maximum value and some lesser value. When one of these variable loads is at its maximum value, the other variable loads are assumed to be at an “arbitrary point in time” value which is less than the maximum. Thus in the ASCE 7 load combinations, the full values of two or more transient loads are never combined in one load combination. Only permanent loads are included at their full value in all ASCE 7 load combinations.

To use this same philosophy to develop load combinations which include the additional primary power plant loads, those loads must be classified, except that instead of considering the power plant loads as “permanent or transient,” they will be classified as “sustained or transient.” All loads which are continuously present during normal operation of the plant should be considered “sustained” and included at their full value in all load combinations, except for the combinations where maximum uplift is sought.

Ash load

Ash is generated during combustion of solid fuels such as coal and wood. The amount generated depends primarily on the type of fuel being burned. Some of the ash becomes entrained in the combustion gas and is carried downstream of the boiler combustion chamber. Thus, all equipment and ductwork associated with the flue gas train downstream of the boiler is susceptible to ash buildup. This includes the flue gas ductwork, selective catalytic reactor (SCR), air heater, sulfur dioxide (SO₂) scrubber vessels and particulate-control devices such as electrostatic precipitators and fabric-filter dust collectors (baghouses). A lesser amount of ash may also be present in the air ducts ahead of the boiler, due to leakage through the airheater.

In some locations, the maximum amount of ash accumulation can be fairly well defined, such as in the hoppers at the bottom of a baghouse. In other locations, such as on horizontal surfaces within the gas ducts, the amount that will settle out of the gas stream and accumulate depends on several factors, including the velocity of the flue gas and the arrangement of the ductwork and equipment. Where ash does accumulate, it does so gradually and is normally not evenly distributed throughout the duct. Ash load in ductwork is thus a variable value, and in this respect it is similar to live load. However, ash load differs from live load or transient load in that it is more permanent in nature. Unless some type of positive ash removal system is included with the equipment, ash load once present does not typically reduce until an outage occurs and the equipment or ductwork can be cleaned. Therefore, in combining ash load with other more transient loads, the ash load should not be reduced to an arbitrary-point-in-time value when one of the other loads is at full magnitude. Instead, ash load should be treated as a sustained load, and its full value used in all load combinations.

The design ash load is typically specified as a uniform load on all horizontal surfaces. Currently there is no industry-wide standard giving recommended minimum ash loads for the various types of fuels, and the design values are determined on a project-by-project basis. Some guidance can be found in the ASCE publication The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications. The boiler equipment manufacturers normally have their own standard loadings based on their experience and historical data, as do the various utilities and/or architectural/engineering firms involved. Consequently, design ash loads can vary considerably from project to project, even those which involve similar types of fuels.

Sustained pressure and transient pressure forces

All of the ductwork and equipment within the boiler system operates under positive or negative pressure. The flows of combustion air into the boiler and combustion gas out of the boiler and through the back-end pollution control equipment occur because of pressure differentials. Modern units normally operate under a “balanced draft” pressure system. In a balanced draft unit, the ducts bringing air into the boiler are normally at a positive pressure due to the forced draft (FD) fans and primary air (PA) fans at the upstream end, while the ducts taking the combustion gases out of the boiler and through the pollution control equipment are normally under a negative pressure due to the induced draft (ID) fans plus stack draft at the back end. Somewhere in the system, normally within the boiler, is the balance point where the pressure switches from positive to negative.

When a system that is under pressure is completely closed and unrestrained by external supports, all stresses caused by the pressure are internal to that system, and no external forces are generated on the supporting structure. However, when there is an opening in the system, an unbalanced pressure force is produced, which must be resisted by the supports. The ductwork which conveys the combustion air and gases is normally divided into sections by expansion joints at various locations, to control thermal expansion and differential movements. Expansion joints are also typically provided at the inlets and outlets of the major equipment within the system, such as the fans, the boiler and economizer, the SCR, air heaters, scrubbers, etc. Internal pressure stresses
are not normally transferred across these expansion joints, and thus they act as openings in the system. Depending on the arrangement of the system and the expansion joints, unbalanced pressure may produce forces on selected supports on either side of the joint. The system manufacturer will determine the magnitude of unbalanced pressure forces and at which supports the forces are transmitted into the supporting structure.

The structural engineer will normally be given two types of pressure loads by the equipment manufacturer: forces due to sustained pressure (sometimes called continuous design pressure) and forces due to transient or excursion pressure. The sustained pressure is the expected operating pressure plus some margin, and is considered to be continuously present during operation of the boiler. The transient pressure accounts for short-term surges in pressure due to an unusual condition.

Sometimes the structural engineer will be given forces for both a sustained positive and a sustained negative pressure condition at all locations. There will thus be primary load cases for both sustained positive and sustained negative pressures. In the boilerhouse though, these two cases alone will not capture the actual conditions which occur. As previously discussed, the normal operating condition has the ductwork and equipment upstream of the boiler under positive pressure and the ductwork and equipment downstream of the boiler under negative pressure. Since the boilerhouse supports both systems, the structural engineer should include a pressure load case which combines the sustained positive pressure loads from the ducts and equipment ahead of the boiler with the sustained negative pressure loads from the ducts and equipment beyond the boiler.

For transient pressure loads, both positive and negative values will always be provided. For the transient positive pressure case, apply the positive pressure loads throughout the structure, and for the transient negative pressure case, apply the negative pressure loads throughout.

Forces due to sustained pressure should be included in all load combinations except those which include transient pressure load. Transient pressure load will occur only on rare occasions during the life of the structure, making it similar to wind load or earthquake load. For this reason, it does not need to be combined with wind or earthquake loads, just as wind and earthquake are not combined together in any of the ASCE 7-10 load combinations. When combining transient pressure load with other transient loads, the same philosophy is used as with other combinations of transient loads in ASCE 7-10; that is, when full transient pressure load is present, the other transient loads are considered to be at some “arbitrary point-in-time” value.

Friction forces

Much of the equipment in power plants operates at a temperature well above ambient. This equipment expands as it heats and contracts as it cools. If the expansion or contraction is resisted, such as by friction at load-bearing supports, thermal stresses will develop in the equipment which will cause forces on the supporting structure at the equipment supports.

To minimize the thermal stresses in the equipment and the resulting forces on the supporting structure, the supports are typically arranged to minimize the restraint to thermal movement. When the equipment is bottom-supported, low-friction bearings are normally provided underneath the load-bearing supports. These bearings allow the supports to slide relative to the support structure during expansion or contraction of the equipment, thus limiting the stresses to those caused by the frictional resistance of the bearings. As the equipment heats or cools, thermal forces will increase until the static coefficient of friction is overcome and the support slides. This static friction force value is what is typically provided to the structural engineer. Once the support slides, the friction force reduces to the value caused by the sliding coefficient of friction. The sliding friction force remains at the end of each cycle; it may eventually dissipate over time but the rate of dissipation is unknown. Considering this, it could be appropriate to consider only the sliding friction force as a sustained load, included in all load combinations. The full static friction force could be considered a transient load. Generally though, this is not done; for simplicity most designers simply use the full static friction force as the sustained force.

Boiler loads

The boiler manufacturer will provide the boiler loads to the structural engineer. For top-supported boilers, there will be vertical rod loads to the top steel and horizontal tie loads at various locations down the boiler walls. There is currently no industry-wide standard for calculating and reporting boiler loads; each manufacturer will have their own system. Rod loads may be reported for two conditions: boiler operating condition and boiler hydrostatic condition. The operating condition includes the loads that exist during normal operation, and should thus be considered a sustained load case. The hydrostatic condition includes the water weight when the boiler is completely filled with water, such as during hydro-testing of the unit or during long-term wet storage. Hydro-testing is a short-term condition, but due to the potential for long-term storage it is prudent to consider the boiler hydrostatic loads as sustained, although they need not be combined with other operating loads such as pressure or friction forces.

Whichever way the rod loads are presented, the structural engineer must make sure that the dead weight of the boiler is separated so that it can be included under the permanent dead load case. The remaining operating loads and hydrostatic loads can be input as two separate primary loads.

Boiler tie forces are caused by furnace pressure, wind (if the boiler is exposed to wind), and earthquake. As discussed earlier, the earthquake forces in the ties must be calculated using a combined seismic analysis as required by Section 15.3 of ASCE 7-10.

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Developing Load Combinations with Power Plant Loads

To determine the maximum design loads for power plant structures, the basic load combinations found in Chapter 2 of ASCE 7-10 must be expanded to include the additional power plant primary loads. The expanded load combinations must maintain the same basic philosophy behind the ASCE 7 combinations, as previously discussed. This has been done in the suggested load combinations which follow, except that instead of considering loads as “permanent or transient,” they have been classified as “sustained or transient.” All loads which are considered “sustained” are included at their full (or maximum factored) value in all load combinations, except for the combinations where maximum uplift is sought.

The author has considered the sustained loads to include dead load, collateral dead load, ash load, sustained pressure load, boiler operating load, and friction load. Boiler hydrostatic load is also considered a sustained load to account for the possibility of a long-term wet storage condition, although it is not combined with other operating loads.

Suggested Nominal Load Combinations for ASD Methods

In the ASCE 7-10 nominal load combinations, all permanent loads receive a load factor of unity, as do the variable loads when only one is being considered. When two or more variable loads are considered together, each receives a load factor of 0.75. This methodology has been used to expand the ASCE 7-10 nominal load combinations to include the additional power plant loads, treating sustained loads as permanent and transient loads as variable.

An appropriate load factor must be determined for transient pressure load in load combinations. Currently there is no statistical data available that indicates how often the transient pressures occur during the operation of the plant, or how often the design transient pressures are exceeded. Lacking this data, the author has simply considered that, in past practice with allowable stress design, a 33% increase in allowable stresses has been used with transient pressure loads. Thus, in ASD load combinations the load factor on transient pressure has been set at 0.75 (equal to 1/1.333).

Nominal Load Combinations for Allowable Strength Design (ASD)

1. \( D + Dc + A + Bo + Ps + Fr + L \)
2. \( D + Dc + A + Bo + Ps + Fr + (Lr or S or R) \)
3. \( D + Dc + A + Bo + Ps + Fr + 0.75L + 0.75(Lr or S or R) \)
4. \( D + Dc + A + Bo + Ps + Fr + (0.6W or 0.7E) \)
5. \( D + Dc + A + Bo + Ps + Fr + 0.75L + 0.75(0.6W) + 0.75Lr or S or R \)
6. \( D + Dc + A + Bo + Ps + Fr + 0.75L + 0.75(0.7E) + 0.7SS \)
7. \( D + Dc + A + Bo + 0.75Pt + Fr \)
8. \( D + Dc + A + Bh + L \)
9. \( D + Dc + A + Bh + (Lr or S or R) \)
10. \( D + Dc + A + Bh + (0.6W or 0.7E) \)
11. \( D + Dc + A + Bh + 0.75L + 0.75(0.6W) + 0.75(Lr or S or R) \)
12. \( D + Dc + A + Bh + 0.75L + 0.75(0.7E) + 0.7SS \)
13. \( 0.6D + Ps + Fr + 0.6W \)
14. \( 0.6(D + Dc + Ab + Bo) + Ps + Fr + 0.7E \)
15. \( 0.6D + 0.75Pt + Fr \)

Footnotes:

a: For the boilerhouse structure, do not include Ps or Fr in load combination 13. The worst uplift condition under wind for the boilerhouse will occur when the unit is shut down and the boiler is empty.

b: In load combination 14, it is assumed that ash load is included in the total mass used to develop seismic forces. If otherwise, do not include ash in resistance to uplift.

Thoughts on Developing Factored Load Combinations for Load-and-Resistance Factor Design (LRFD)

Section 2.3.6 of ASCE 7-10 specifies requirements that must be met when developing factored load combinations for use with strength design methods, when the primary loads are not specified in ASCE 7-10. This is the case for the loads specific to power plants. Section 2.3.6 permits a design professional to develop the factored load combinations, but requires the use of a method that is consistent with the method that was used to develop the basic factored load combinations found in Section 2.3.2. The design professional must use a probability based method, based on load data that has been collected and statistically analyzed to determine a mean value and coefficient of variation. See the Commentary Section C2.3.6 in ASCE 7-10 for further guidance.

Such collected load data for the types of power plant loads we are discussing does not currently exist. In addition, there are currently no industry-wide standards for ash load, nor are there standardized procedures for developing pressure loads. Thus it is not possible at this time to develop the factored load combinations that comply with the requirements of ASCE 7-10 Section 2.3.6 when power plant loads are included. Further work is required to collect the necessary data on these loads, to develop standards and perform the statistical analysis required to determine appropriate load factors.

Symbols

- \( A = \) ash load
- \( L = \) live load
- \( Bo = \) boiler operating load
- \( Lr = \) roof live load
- \( Bh = \) boiler hydrostatic load
- \( Pt = \) transient pressure load
- \( D = \) dead load
- \( Dc = \) collateral dead load
- \( R = \) rain load
- \( E = \) seismic load effect
- \( S = \) snow load
- \( Fr = \) friction load
- \( W = \) wind load
References

• American Society of Civil Engineers (ASCE). (2010). Minimum Design Loads for Buildings and Other Structures (7-10).
• American Society of Civil Engineers (ASCE). (1995). The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications, published by the Air and Gas Duct Structural Design Committee of the Energy Division of the American Society of Civil Engineers.
• American Society of Civil Engineers (ASCE). (2011). Wind Loads for Petrochemical and Other Industrial Facilities, published by the Task Committee on Wind Induced Forces of the Petrochemical Committee.