The Effect of a Tornado on Nuclear Power Plant Structures

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ABSTRACT

The structural systems of some nuclear power plants were designed on the basis of local building codes which did not contain provisions considering the effects of tornado loadings. Since the construction of these plants, the Nuclear Regulatory Commission has issued Regulatory Guide 1.76, which defines a design basis tornado (DBT) accounting for the various loadings that occur during a tornado strike. Due to the concern regarding the extent to which older plants can satisfy these licensing criteria, the Nuclear Regulatory Commission, as part of the Systematic Evaluation Program (SEP), initiated a study to investigate and assess the safety of existing structural designs.

The paper reports the findings of the SEP study in interpretating and applying the DBT regulatory criteria. The adequacy of general structural designs, components, and details to meet current requirements is discussed. The relative importance of the various tornado loading phenomena are reviewed. The typically weak design elements are identified along with the mechanisms of failure. The paper concludes with a discussion of various special problems encountered in applying the regulatory criteria.

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*The views expressed in this paper are those of the authors. The technical contents of this paper have neither been approved nor disapproved by the U.S. Nuclear Regulatory Commission.

1. Introduction

Some nuclear power plants were constructed and licensed for operation before a tornado strike became a design requirement. Although some of these plants included tornado loadings as a design criteria for containments and other structures, the majority of the structural designs were based on the wind loading provisions of state and local building codes which did not account for the effects of tornadoes. The design basis tornado is now defined as an extreme environmental event [1, 2], and guidelines governing tornado-resistant design are part of the Standard Review Plan [3, 4].

As part of the Nuclear Regulatory Commission's Systematic Evaluation Program (SEP), a study was conducted to evaluate the tornado resistance of existing plant structures at nine SEP plants. The study centered on finding the threshold windspeeds at which building components failed, and used the Standard Review Plan guidelines to judge the capacity of structural elements and to convert the various physical phenomena associated with a tornado into structural loadings. The original design of two of these plants included tornado loading provisions, and both of these plants performed well in this study. As expected, the majority of problems arose for plants that were not originally designed for tornadoes. The study was conducted by first analyzing two plants, a boiling water reactor (BWR) and a pressurized water reactor (PWR). These analyses were then used as models by the remaining seven plant owners in analyzing their facilities. Those results were submitted and reviewed with respect to assumptions, methodology, and criteria, and independent analyses were performed on selected structures to verify structural capacities. This paper presents the general findings and conclusions of that study.

Throughout the study, it has found that the containment structures (steel spheres, concrete cylinders and domes, and the part of the reactor building below the operating floor of boiling water reactors) have adequate capacity to resist tornado loadings. Therefore, this paper focuses primarily on the other Category 1 structures [4].

2. Loadings

The critical tornado parameters are the maximum windspeed, the distribution of windspeed, the maximum atmospheric pressure drop, and the rate of atmospheric pressure drop. Windspeeds can be directly converted to dynamic pressures which give rise to two kinds of structural loading: a frontal wind pressure or positive pressure, due to the momentum of the air particles confronting a structure, and a differential pressure or negative pressure (suction and uplift) caused by the flow of air particles over, around, or into a structure. The magnitude of these pressures acting on various parts of a structure is readily calculated through the use of shape coefficients [5, 6]. A third load, which is equivalent to a differential pressure loading, is due to the local atmospheric pressure drop, a situation occurring primarily in the core of the tornado. Another kind of loading due to tornadoes, the impact of windborne missiles, is not considered here.

Dynamic pressure loads can act on any exposed part of a structure. Loadings due to the atmospheric pressure drop will also act on surfaces that are shielded from wind flow but are still exposed to the atmosphere (i.e., closely spaced walls of adjacent buildings). If the skin elements (exterior walls and panels) of a structure fail, then all of the loads, albeit at a reduced magnitude, can act on interior structural components.

As a tornado traverses a site, there is a time variation in the magnitude of the dynamic pressure and the atmospheric pressure drop that results in the dynamic loading of structural components. However, the time rate of these loadings is low compared to the structural natural periods and, except for special configurations, these loads can be considered statically applied.

The study assumed that snow loads do not act during a tornado strike and that the soils of a site are unaffected by the winds and changing pressures and remain intact around foundations.

Analysis was performed on the basis of linear elastic modeling. The reserve strength of steel elements under extreme environmental loads was accounted for by increasing the allowable stress levels above the standard code limits. Concrete capacities were obtained using ultimate strength methods and the specified strength values of concrete and reinforcing steels.

An additional complication to the analysis was the need to review various scenarios of loading and failure. This is a complication because:

1. Individual structural components are generally not equally resistant to all the tornado loadings.

2. Failure of adjacent minor structural members can seriously affect the capacity of important intact members.

3. Failure or loss of function of some structural components can drastically change the flow of loading throughout a structure.

These effects interact with one another, and the reviewer is faced with the challenge of postulating and examining different sequences of loading in formulating the most critical scenarios.

3. Roofing Systems

The most stringent loading condition for roofing systems is uplift due to an atmospheric pressure drop. When mechanisms are provided for relieving this loading, their action must be carefully examined to see if they will be active for all imaginable tornado strikes. A tornado is a highly localized windstorm and it is conceivable that a part of a structure will escape being hit or will be subjected to positive pressure while another part of the structure experiences a sequence of positive and negative pressures. Also, even though internal pressures may be relieved through venting or the destruction of side walls, local roof sections can still experience uplift forces due to dynamic pressures. Only if a roof is particularly light and flexible will the dynamic loading effects of uplift pressures become critical.

Concrete roofing systems consist of slabs cast and tied into concrete roof girders. Uplift loads cause the major steel reinforcement of these sections to be in the compressive zone, and in some slab designs, there is virtually no steel in the tensile zone. However, the dead load of the concrete greatly assists in the uplift resistance of these components, and it was found that typical designs were acceptable.

Some concrete roof decks are supported by steel girders or trusses. Again, the dead weight of the concrete greatly assists in the resistance of the whole unit. Areas of concern are the beam seat connections, the beam seat elements, the slab-girder connections, and the steel members. As a complete system, these components were found to have high strength against uplift loadings.

Steel roofing systems consist of steel decks or concrete planks supported by structural steel beams framing into girders or trusses. The dead weight and section modulus for steel decks is minimal, so these elements have low resistance to uplift loadings and, where adequate connections have been provided, they will fail by flexural buckling. This does not imply that the loads on the underlying roof steel are completed relieved, and the assumption that the roof deck "blows out" should be carefully examined. Incomplete blowouts mean that parts of the roof may still be loaded as the deck and fasteners enter a plastic state. Concrete roof planks with a higher weight and section modulus have a substantially higher resistance.

Roof steel beams are particularly sensitive to uplift loads because the bottom flange of a roof beam, which in all likelihood is unbraced, is placed in compression. The large unbraced length of these members leads to a substantial reduction in bending capacity. Also, many roof beams perform a double function as axially loaded members of bracing systems. Since the magnitude of the axial loads is greatly increased during a tornado strike, the interaction of this load with the uplift loading leads to remarkably low tornado resistance. Where roof beams are adequately braced and have moderate tributary load area, the roof steel system has high tornado resistance under the governing structural acceptance criteria.

In roof bracing, the capacity of the entire system is not reached when the weakest component has reached its limiting strength, and designers can account for the fact that a buckled section does not imply loss of function. Note that some designs rely on roof decking to provide bracing. For tornado loadings, this is not good practice due to the flexibility and weakness of these elements.

4. Building Skin Elements

Masonry block construction, with and without reinforcing bars, composes the walls of many of the examined nuclear plant structures. There are no unusual tornado loadings combinations associated with these systems, and dynamic loading effects are not critical for normal geometries. The analytical modeling of these simple components depends on the connections at the wall boundary. The bottom courses of block are usually tied down to the floor slabs with anchor bolt and plate arrangements, while the top courses are laid to the adjacent structural framing to which the wall is attached with bolts or bent tie connections. Some heavier designs include steel plates which directly tie the block wall to frame members along each boundary. For most arrangements, the walls can be modeled as simply supported for positive pressure loadings. In cases where the top of walls are provided with widely spaced weak connections, reaction forces will not be transferred to the underlying frame members for walls under negative pressure loadings. In this situation, it is appropriate to use a cantilever beam model.

In the beam models, the dead weight of the wall assists in counteracting the tensile stresses at a section. Also, extreme environmental factors can be applied to code allowable stress values [7]. In all designs, the adequacy of the underlying structural members to resist the wall reactions must be examined. In some cases, the limiting component of the wall system was found to be support steel beams bent about the weak axis by wall reactions. Multi-wythe construction can be modeled as a single beam (as opposed to multiple beams) if shear stress levels between the wythes are not excessive. Some designs which include horizontal as well as vertical reinforcement could be examined as a plate if the connections are adequate.

Another frequently used skin element is structural siding which consists of a fascia (a contoured outer surface) and a liner separated by a layer of insulation and bound together in successive panels by overlapping and button punching. The complete panels are fastened to girts by panel clips and screws. This construction leads to unique loadings and difficult modeling decisions [8]. Depending on the adequacy of the binding between the fascia and liner, it can be assumed that they either act independently or have compatible displacements. The most conservative approach is to assume that the fascia resists the full negative and positive pressure loadings. The failure mechanisms to be checked are flexural buckling, fastener clip failure, fastener yielding, and punchout failure. The steel girts can also be limiting, especially if they are channel sections without substantial connections to the structural frame.

Failure of the skin exposes the interior mechanical, electrical, and structural systems to the tornado loadings. If these systems are attached to or located adjacent to the building skin, they will be affected by the structural debris. Such loadings can lead to loss of function or failure of these components.

5. Structural Frames

The magnitudes of the loads experienced by the structural frame are dependent on the integrity of the building skin elements. However, if the skin fails, not all of the load is necessarily released since configurations of failure can be conceived which will substantially load individual column and beam members [9].

Most heavy steel members have high tornado resistance. Problems occur when unexpected load combinations and altered structural configurations arise. Examples of such cases are unplanned weak axis bending of columns and the buckling of secondary bracing members. It is important to examine the structural mechanisms for transferring lateral loads from unbraced frames to braced frames. In most cases, the main lateral force resisting frames have sufficient strength, but the mechanism for transferring the loads to these systems (load path) has not been adequately investigated and designed. As a result, it is frequently found that columns must assist in resisting lateral loads by bending which, in addition to the acting axial loads, may lead to a critical section. Beams also are called on to resist wind-induced axial loads outside of the intentions of the original design. Since many designers size cross bracing on the basis of the tensile section, structures have the built-in reserve to resist the lateral wind loads by the post-buckled strength of compression members.

As expected, concrete construction with thickened wall and floor slabs, such as the parts of the boiling water reactor building located beneath the operating floor, is highly resistant to tornado loads. Such structures are particularly effective in resisting lateral loads as external forces are readily transferred to internal structural components. For stand-alone walls (usually supporting steel systems as in control rooms, radwaste buildings, and generator rooms), this is not the case and these structures require review. Concrete panels and walls should be checked for the level of reinforcement on both faces since some walls are weak under negative pressure loadings. Finally, the tornado loadings can produce tensile stresses in some unexpected areas which should be thoroughly examined in concrete frames.

6. Special Problems

The Standard Review Plan includes chimneys and vent stacks in Section 3.8.4, "Other Category 1 Structures" [4]. This section specifies ACI 349 as the applicable concrete code and specifies capacities based on ultimate strength for extreme environmental loads. The American Concrete Institute code provisions [10] call for working stress designs for chimneys until further experimental work is conducted. Chimneys at nuclear power plants are not necessary to achieve safe shutdown; however, concerns arise if their failure affects Category 1 structures. In this review, as a comparison, one chimney was examined using the rationale of both design methods as well as a procedure which employed working stress methodology with increased stress allowables [11]. The ultimate strength method predicted the chimney would be able to resist the full design basis tornado, whereas the other two methods predicted moderate chimney resistance.

Additional concerns related to chimneys are vortex shedding and ovalling. While ovalling does not seem to cause structural difficulties, the frequency of vortex shedding should be examined for possible dynamic loading. Also, the foundations and soil capacities under these structures can be critical and should be reviewed.

Another problem is that the original design wind loading models on some cylindrical and spherical containment structures do not accurately depict the distribution of the pressure loads. Although it is felt that, for the most part, the original design distribution will lead to conservative results, each individual design requires review.

Much of the guidance given for tornado-resistant design is based on the extrapolation of rules used in normal wind loading designs [5, 6]. These design methods were not intended to address tornadoes and it can be argued that some aspects of their provisions, such as the use of shape factors in calculating pressure loadings, may not be totally applicable to tornado loadings. (The shape factors and pressure calculations are based on wind tunnel tests conducted with smooth, low velocity air flows and validity of extrapolating test results to high velocity turbulent flows has not been established.) Although research will bring improvements to tornado modeling, it is felt that the present design criteria result in structures with high resistance to tornado loads.

The regulatory criteria specify the design basis tornado based on a plant's geographical location. The country has been divided into three regions, each of which encompasses large areas with varying characteristics. For each region, a design basis tornado is specified. Regulatory provisions permit site studies to identify in a probabilistic sense more accurate tornado parameters (as has been done in a separate SEP effort for the plants in this study). The regulatory criteria also do not differentiate between the likelihood of various loading scenarios occurring. Again, a site study may reveal that some loading scenarios have little or no chance of occurrence. In dealing with such information (velocity distributions, direction of strike, possibility of shielding, etc.), it might be meaningful to construct probabilistic models that use probability of exceedance criteria to yield probabilistic conclusions on structural strength. This could be extended to determine probabilistic conclusions regarding the occurrence of unacceptable consequences. Whether probabilistic or deterministic models are used, site-specific information greatly influences the final decision on structural adequacy.

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