Nonlinear structural dynamics for assessing aircraft impact at nuclear power plants

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ABSTRACT: The next generation of nuclear power plants is being designed worldwide with consideration for the effects of impact from a large commercial aircraft as a malevolent act. Detailed, realistic nonlinear structural analyses are required to assess the physical damage caused by an impact in order to meet regulatory requirements. In the U. S., industry developed methodology for conducting aircraft impact analyses have been accepted by the U.S. Nuclear Regulatory Commission (NRC) and requires advanced constitutive modeling of reinforced concrete, detailed and realistic structural modeling, appropriate material failure criteria, and realistic application of the impact load using robust explicit dynamics analysis software. The most common approach for load application is the Riera method that uses a force time history applied over a representative contact area as a pressure load. Sample studies demonstrate that the Riera method offers good analytical results for structural configurations that can fully resist the impact. For structural configurations that are insufficient to withstand the impact forces, the Riera method is useful for assessing the failure mode of the impacted wall, but the method fails to quantify the consequences of aircraft debris that penetrates beyond the initial point of impact. The sample studies also demonstrate that for some cases the design-basis structure can adequately meet aircraft impact requirements. For other cases where reinforcement is minimal or the span of the impacted wall is large, design enhancements can be made to offer the necessary resistance to limit damage to the exterior wall. If the impacted wall fails, the consequences of debris entering the plant can be determined by an alternative approach for load application called the missile-target interaction method. Further sample studies demonstrate that with this approach, the aircraft can be explicitly modeled and used to investigate a realistic extent of damage, which may be acceptable.

KEY WORDS: Aircraft Impact; Nuclear Power Plants; Nonlinear Structural Dynamics; Advanced Concrete Material Modeling.

1 INTRODUCTION

The next generation of nuclear power plants is being designed worldwide with consideration for the effects of impact from a large commercial aircraft as a malevolent act. Nuclear power plants have always had extremely robust designs considering impacts from accidental and natural causes, such as tornado driven debris or missiles generated from failures in high energy systems within the plant, and even military aircraft if sited near areas of frequent military maneuvers. Nuclear plant designs also consider what if scenarios for large fires or explosions from any cause that could damage an area of the plant.

The new standards for consideration of intentional impacts from large commercial aircraft are requiring detailed structural modeling for damage assessments and detailed system engineering assessments to quantify the consequences. These structural and systems assessments are used to identify design enhancements, if needed, for the plant to mitigate the consequences of aircraft impact and maintain the plant in a safe condition with minimal operator actions. This paper focuses on the methods needed for assessing structural performance in regards to aircraft impact.

2 METHODOLOGY

2.1 Structural Assessment Methods

The Nuclear Energy Institute (NEI) has issued document number NEI 07-13 [1] that addresses methodology for performing aircraft impact assessments of nuclear power plants. A critical ingredient in the assessment of structural response to aircraft impact is the constitutive model for reinforced concrete, which must be highly detailed in its representation of material behavior and numerically sound to permit the calculation of severe damage. Also important is a numerically robust explicit dynamics platform for capturing eroding contact surfaces, managing rebar and concrete interaction under severe cracking, and allowing efficient computations of large problems. For this work, the ANACAP concrete material model [3] coupled with the TeraGrande explicit dynamics software [4] are employed. The concrete material model has been extensively tested for loading leading to extensive damage in reinforced concrete [5,6,7,8,9]. This model was used extensively in EPRI research studies as the basis for the structural methodology incorporated into NEI 07-13, and is explicitly accepted for use in NEI 07-13.

2.2 Advanced Concrete Material Modeling

The behavior of concrete is highly nonlinear with small tensile strengths, shear stiffness and strength that depend on crack widths, and compressive capacity degradation after the compressive strength is reached. Modeling of concrete material, especially under conditions where extensive damage can develop, requires advanced and detailed constitutive models.

In the compression regime, the continuous stress-strain curve is defined from uniaxial test data, which is then
generalized to multi-axial stress/strain states in the conventional way using the effective stress and the effective strain. The uniaxial behavior is generalized to multi-axial behavior, within the analytical framework of isotropic-hardening plasticity formulation, using a Drucker-Prager surface to represent the loading surface under multi-axial compression. In this formulation, the loading surface is a function of the hydrostatic pressure, the second invariant of the deviatoric stress tensor and the material yield strength. This type of formulation is well suited for low to moderate confinement stress levels, which typifies the behavior of civil structures. Typical stress-strain curves for concrete under monotonic and unconfined uniaxial compression show linear behavior up to about 50% of its uniaxial compressive strength. For stresses above this level, the material exhibits strain hardening until it reaches its ultimate strength. When the compressive strains are increased further, damage due to crushing continues to accumulate, thus causing rapid strain softening. Figure 1 shows the strain hardening and softening behavior of the model for unconfined uniaxial loading. Highly confined concrete exhibits considerably more strength and ductility. For situations where significant concrete confinement exists, such as impact on pre-stressed concrete containments, the compressive concrete behavior is better simulated using non-softening plastic flow since the material can sustain larger compressive strains as well as increased compressive strength.

In the tension regime, cracking is mathematically treated at the element integration points using an approach that is called the smeared cracking model [10]. If cracking occurs, the normal stress across the crack is reduced and the distribution of stresses around the crack is recalculated. Cracks are assumed to form perpendicular to the directions of largest tensile strains, which exceed the cracking criterion. Multiple cracks are allowed to form, but they are constrained to be mutually orthogonal. Once a crack forms, the normal stress across the crack is removed. The shear stiffness and stress is also reduced upon cracking and further decays as the crack opens. Once a crack forms, the direction of the crack remains fixed and can never heal. However, a crack can close, resist compression, and re-open under load reversals.

The concrete material model allows cracking to develop in three directions at any material point as dictated by the state of stress and strain. This allows stress redistribution and load transfer to reinforcement or other load paths in the structure. The cracking criterion, illustrated in Figure 2, forms a crack when the generalized stress and strain state normal to the crack exceeds the diagonal criterion line. Thus, cracking of biaxial and triaxial stress states are treated consistently with uniaxial cracking, but they occur at a slightly higher stress and slightly lower strain. Split cracking occurs at near zero stress and a tensile strain approximately twice that of uniaxial tensile cracking. This agrees well with the observed behavior of concrete test specimens.

The surfaces of cracks that develop due to excess tensile stress in concrete are usually rough and irregular. When a shear force is applied along a crack, both tangential shear sliding and normal displacements result. When the normal displacement is restrained by rebars crossing the crack, tensile stresses will develop in the reinforcement, which will then induce compressive stresses across the crack. The resistance to sliding is provided by the frictional force generated by the compressive stress across the crack. This mechanism of shear transfer in cracked concrete is called "interface shear transfer". In order to take the shear stiffness of concrete into account in the modeling, a reduced shear modulus is retained in the stress-strain matrix. Al-Mahaidi [11] suggests a hyperbolic variation of the shear modulus with the strain normal to the crack, and a variation of this is used in the ANACAP concrete model, as illustrated in Figure 3.

An important modeling consideration is the treatment of shear stress across open cracks. The ANACAP model is equipped with a shear shedding feature to limit the buildup of shear stress across an open crack. The shear retention model
reduces the incremental shear modulus across an open crack as discussed earlier. The shear stresses that can be accommodated across an open crack also reduce as the crack continues to open. Since cracks form in the principal strain directions there is, in general, no shear across a crack when it first opens. Figure 4 illustrates the behavior of shear stress capacity in cracked concrete for a tight crack, for example cracking well controlled by reinforcement, compared to a crack that continues to open.

Figure 4. Illustration of Shear Capacity for Open Cracks

### 2.3 Material Properties and Failure Criteria

Impact of large commercial aircraft due to malevolent act is considered a beyond-design-basis event and is thus treated using best estimate methods rather than design minimum standards. The material properties used in the structural analyses are based on best estimate or nominal values along with factors to account for dynamic loading rate effects. For concrete material, the concrete strength delivered during construction must always meet the minimum compressive strength specified in the design. Thus, the nominal or expected value for the compressive strength is specified in the analysis. In addition, an aging factor can be applied since the plant will not become operational for an extended period of time after construction is completed. A 25% increase in compressive strength is also allowed for rate effects due to the impulsive nature of the loading. Similarly, steel material properties are based on nominal values of yield and ultimate strength along with dynamic increase factors for strain rate effects. Steel behavior is based on typical nonlinear stress-strain relationships for strain hardening of the material.

Because extensive structural damage can occur and is allowed for beyond design basis events, specification of material failure criteria is important in the structural assessments to determine the extent of damage to the structure. For concrete, the material limit states are enforced by the concrete material model, e.g. very small tensile strength, shear stiffness and strength as a function of crack opening strain, and compressive plasticity. In addition, element deletion is enforced for 5% tensile strain or 10% compressive strain in the concrete material. Similarly, failure criteria for steel material are enforced that accounts for meshing fidelity and biaxial loading effects. Table 1 summarizes the dynamic rate factors allowed for common steel material and the associated failure criteria to be enforced.

<table>
<thead>
<tr>
<th>Material</th>
<th>Rate Factor</th>
<th>Failure Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 60 Rebar</td>
<td>1.10</td>
<td>5% Tension</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td>10% Compression</td>
</tr>
<tr>
<td>Carbon Steel Plate</td>
<td>1.29</td>
<td>7% Effective Compression</td>
</tr>
<tr>
<td>Stainless Steel Plate</td>
<td>1.18</td>
<td>13.8% Effective Strain</td>
</tr>
</tbody>
</table>

### 2.4 Loading Methods

The methodology for structural response assessment allows two methods of applying the load representative of an aircraft impact; one is based on the Riera method using a force time history applied over a representative contact area, and the other is called the missile-target-interaction method where a model of the impacting aircraft is explicitly included in the analysis. Experience [12,13,14,15] has shown that using time-dependent pressure loading, based on specified force-time histories and loading areas, provides good results when sufficient structural resistance exits, and also provides a good indication that structural failure will develop when sufficient resistance does not exist. For conditions leading to structural failure, the analysis using applied pressure loading is also capable of identifying the mode of failure, such as bending, shear plug, compressive strut, plastic hinging, etc. However, continuing the pressure load analysis past the point of extensive structural damage or failure to assess the subsequent extent of damage or structural consequences is possible, but relies heavily on engineering judgment to establish the time of failure or remaining momentum and how to subsequently define and distribute this remaining momentum on the surrounding structural components. When extensive structural damage develops, such as failure of the impacted wall, an explicit model of the aircraft is preferred in the structural analyses to better assess the extent and consequences of the damage. Using an aircraft model that adequately represents the impact event described by the specified force time history and loading areas allows natural progression of damage and redistribution of loads through contact with the structural components and material failure limits enforced in the analysis. Another application for use of an airplane model is for oblique impacts where the strike is off-normal to the surface, such as for a roof strike on a curved roof structure or an angled strike on a flat wall. The key is developing a model of an aircraft that adequately represents the impact loading. This is done by developing a finite element model of an aircraft and then distributing mass points along the length so that impact of this aircraft model on a rigid wall provides a force time history compatible with the desired force time history for a given impact velocity.

### 2.5 Finite Element Modeling

To meet licensing requirements for aircraft impact, it is important that all models accurately represent the actual structure being considered. Aircraft impact assessments involve a large extent of loading, and therefore finite element models must encompass a broad extent of the structure. The size of the model is generally large enough such that the quality of the analytical results will not be adversely affected in the particular area of interest due to an artificial boundary...
condition. The models have boundaries that represent cut sections through walls, floor slabs, girders and columns of the building. Displacement boundary conditions are enforced on these cut surfaces with the intent to simulate the effect of the remainder of the structure that is not included in the model. The cut planes in the vertical direction are generally chosen at locations that coincide with the mid-span of key structural features such as floor slabs and girders. A roller type boundary condition (displacement normal to the surface of the cut) is applied to this type of cut plane. Typically just one cut plane is required in the lateral direction and is generally chosen at the top surface of a floor slab at or near grade. A fully-fixed boundary condition is applied to this type of cut plane to simulate the embedment of the structure into the ground.

The finite element models are constructed using element types that are considered standard practice for explicit dynamic analyses. Concrete components of the structure are modeled with 8-node hexahedral brick elements and reinforcing bars are modeled with 2-node “truss like” elements that are embedded in the solid elements. Each individual reinforcing bar is explicitly included in the model. In addition, 4-node quadrilateral shell elements and 2-node beam elements are used as necessary to model other components of the structure.

3 STUDY ASSESSMENTS

Example results are provided to illustrate the methods employed for aircraft impact assessment. The loading used in these studies is arbitrary and was developed to demonstrate the modeling and analysis methodology; however, it is considered representative of a large commercial aircraft. Similarly, the structural configurations considered are arbitrary and for illustration only, but are considered representative of typical reinforced concrete configurations used in nuclear power plants.

3.1 Finite Element Study Model

A single finite element model was constructed with large enough extents so that multiple strike locations could be considered to demonstrate a variety of structural configurations and impact scenarios. The geometry of this particular model is arbitrary but is representative of the spent fuel pool (SFP) area of a typical nuclear power plant. An illustration of the finite element model is provided in Figure 5 showing a cut section view of the complete model. Two strike locations are considered for the study cases which are indicated in the figure with red arrows.

The lower strike location is positioned vertically at the midpoint between floor slabs and laterally at the midpoint between transverse interior walls. This impacted bay is representative of a typical size wall that spans one floor vertically and about two to three times this distance in the lateral direction. The upper strike location is positioned at the midpoint of the span of the external wall above the spent fuel pool. This impacted bay is representative of a large size wall and is therefore particularly vulnerable to aircraft impact.

Figure 5. Section Cut View of Finite Element Study Model

The rebar included in the finite element model is illustrated in Figure 6, which shows the complete model. The reinforcement considered in the impacted wall varies depending on the strike location and is discussed later for each corresponding scenario. All of the other concrete components in the model include a nominal amount of reinforcement that is consistent with typical reinforcing schemes for nuclear power plants.

Figure 6. Illustration of Rebar in Study Model

3.2 Strike on Typical Wall Span

This example examines the structural response of a typical sized wall span that can fully resist the aircraft impact loading. The impacted wall contains reinforcement consistent with standard design-basis requirements for the structure. For the purposes of this study, a 5’ thick wall is considered with two layers of bars in each direction and on each face and no shear tie bars. The force of the aircraft impact is applied to the structure with a pressure loading using the Riera method.
An explicit dynamic analysis was performed for a duration that extends beyond the time period of the pressure load to investigate the adequacy of this configuration. The reaction forces in the direction of the applied load were recorded and summed across the entire model. The impulse of the reaction forces was computed and plotted against the impulse of the applied force, which is illustrated in Figure 7. The impulse values are normalized to the total impulse of the applied force, which is equal to the momentum of the impacting aircraft. This figure demonstrates that the structure can absorb the total impulse of the applied load.

Figure 7. Impulse Comparison, Strike on Typical Wall Span using Riera Method Pressure Load

The accumulated plastic strain in the longitudinal reinforcement on the internal face of the impacted wall is illustrated in Figure 8. The contour limit has been set at 2% which is below the failure strain of the rebar. Two horizontal bands of rebar yielding have developed above and below the center of the strike location in positions that correspond to the location of the supporting transverse floor slabs. A moderate amount of damage is caused to the longitudinal bars in the vicinity of the strike location but this figure demonstrates that none of the rebar in the wall is ruptured due to the aircraft impact.

Figure 8. Accumulated Plastic Strain in Rebar, Strike on Typical Wall Span using Riera Method Pressure Load

This study demonstrates that the external wall will survive an aircraft impact at this location, even with a reasonable amount of reinforcement that is feasibly within the existing design-basis of the structure. This study also demonstrates that for structural configurations with sufficient resistance, the Riera method provides good analytical results for damage assessments.

3.3 Strike on Large Wall Span

This example examines the structural response of a large wall span with strengthening measures so that it can fully resist the aircraft impact loading. This type of scenario is of particular interest if all debris and wreckage is to be kept out of the building to meet licensing regulations, therefore the design-basis must be enhanced in order to satisfy this requirement. For this study, the impacted wall is increased to 6’ thick, and the reinforcement considered is three layers of heavier bars in each direction and on each face with medium sized shear tie bars. The force of the aircraft impact is applied to the structure with a pressure load using the Riera method.

A comparison of the impulse of the reaction forces against the impulse of the applied force is illustrated Figure 9. The behavior of the time history of the impulse is generally indicative of the level of damage in the structure. When damage is low, the impulse of the reaction forces tends to closely follow the impulse of the applied force, similar to the impulse response for the strike on the typical wall span. For this case, a shift occurs in the impulse comparison between normalized analysis time 0.3 and 0.4 which suggests heavy damage to the structure. Since the impulse of the reaction forces ultimately achieves the momentum of the aircraft, this indicates that despite the damage, the structure can still absorb the total impulse and survive the applied load.

Figure 9. Impulse Comparison, Strike on Large Wall Span using Riera Method Pressure Load

The displacement history of the concrete at the center of the strike location is provided in Figure 10. The impacted wall undergoes a peak displacement of about 18” with a good amount of elastic recovery, which further indicates that the wall can adequately resist the applied loading. Some residual damage is indicated.

Figure 10. Displacement History of Concrete at Strike Location using Riera Method Pressure Load

1993
Figure 10. Concrete Displacement History under Impact, Strike on Large Wall Span using Riera Method Pressure Load

Figure 11 provides a contour of maximum principal strain in the concrete for a section cut view through the impacted wall. Here the contour limit is set at 2% to indicate the areas with more extensive damage. Large extents of cracking occur on the outer face of the wall extending beyond the diameter of the fuselage. More extensive cracking damage propagates through the thickness of the wall diagonally from the strike location towards the supporting transverse slabs as the wall transfers the load to the supports.

Figure 11. Section Cut View of Concrete Cracking Damage, Strike on Large Wall Span using Riera Method Pressure Load

The accumulated plastic strain in the longitudinal reinforcement on the internal face of the impacted wall is illustrated in Figure 12. The contour limit has been set at 1.5% which is below the failure strain of the rebar. This figure demonstrates that despite the significant rebar yielding in the longitudinal bars, no bars have ruptured, and the bending capacity of the wall has not been fully exhausted.

The accumulated plastic strain in the shear tie reinforcement in the impacted wall is illustrated in Figure 13. The contour limit has been set at 5% which is equal to the failure strain in the rebar. This figure shows the extensive rebar yielding in the tie bars across nearly the entire span of the impacted wall, with some bars exceeding the failure strain and rupturing. This also illustrates the high shear forces involved and provides further evidence that the wall can survive the impact loading.

Figure 12. Accumulated Plastic Strain in Longitudinal Rebar, Strike on Large Wall Span using Riera Method Pressure Load

Figure 13. Accumulated Plastic Strain in Shear Tie Rebar, Strike on Large Wall Span using Riera Method Pressure Load

This example shows that even large span walls can be configured to fully resist the impact forces if needed. For these types of configurations, the design-basis must be enhanced in order to add sufficient resistance. For this example in particular, the addition of dense tie bars to the impacted wall is essential to withstand the large shear forces and maintain the composite action of the R/C wall. The required design enhancements can only be determined by analysis, and with some iteration, an optimized structural configuration can be determined to minimize the added construction costs. This study also further demonstrates that the Riera method provides good results when the wall is able to resist the aircraft impact, even with extensive damage.

3.4 Missile-Target Interaction

For this next example a slightly modified configuration of the typical wall span is considered to demonstrate a scenario where the impacted wall fails due to aircraft impact. The amount of longitudinal reinforcement remains at two layers but the bar size is reduced. The force of the aircraft impact is first applied to the structure with a pressure load using the Riera method and then again with the missile-target interaction method through the use of an explicitly modeled aircraft impacting on the structure.
For the analysis using the Riera method pressure load, a contour of maximum principal strain of the impacted wall at the time point when the first wall is nearing failure is shown in Figure 14. A large circular extent of heavy cracking damage forms on the external face of the wall that is approximately the size of the fuselage. Additionally, a ring of elements has reached the failure strain criteria and have been deleted. The damage pattern clearly demonstrates that the impacted wall is failing due to punching shear.

![Figure 14. Point of Failure, Strike on Under-reinforced Typical Wall Span using Riera Method Pressure Load](image)

The damage in the concrete at the end of the analysis is illustrated in Figure 15 to demonstrate the complete failure of the wall as predicted with the Reira loading method. Furthermore, the accumulated plastic strain in the longitudinal bars on the inside face of the wall is illustrated in Figure 16 to show the extensive rebar rupturing. Although it is difficult to discern the level of damage beyond the failed wall with the Riera method, it does demonstrate that the mode of failure of the wall is captured which is useful for developing design enhancements.

![Figure 15. Residual Damage, Strike on Under-reinforced Typical Wall Span using Riera Method Pressure Load](image)

A finite element model was constructed that is representative of a typical large commercial aircraft and that can be used for the loading. An illustration of the aircraft model is provided in Figure 17. The key geometric features of the aircraft, such as the various lengths, fuselage diameter, and width of the wings, are modeled for consistency with the Riera based force time history. The mass distribution along the length of the aircraft is calibrated to the Riera method force time history by impacting the aircraft model into a rigid wall and comparing the calculated reaction forces with the Riera forces.

![Figure 17. Illustration of Representative Aircraft Model](image)

The previous example case was re-assessed using the aircraft model with an initial velocity consistent with the Riera based force. The analysis software uses a contact tracking algorithm to facilitate the interaction between aircraft and concrete. Figure 18 provides a velocity contour at the point in time when the impacted wall is nearing failure, which is equivalent to the result provided for the Riera method in Figure 14. The velocity contour is normalized to the initial velocity of the plane, which is plotted in red color. This figure demonstrates the crushing of the aircraft as it impacts the wall. The velocity of the rest of the fuselage away from the wall has only slowed by approximately 10% at this time point. Therefore, a large portion of the aircraft is able to pass through the opening caused by the external wall failure and impact subsequent structures inside the building.
A section cut view is illustrated in Figure 19 that shows the extent of wreckage inside the building by the end of the analysis. The velocity contour demonstrates that by this time the momentum of the aircraft is almost entirely stopped with most of the wreckage crushing up against the subsequent interior wall. The tail of the aircraft has rotated slightly upward impinging against the upper portion of the external wall. The consequences of failure of the exterior wall can be assessed by considering the subsequent structural response of the interior walls.

REFERENCES