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Division I

INCREASING ACCURACY IN ULTIMATE CAPACITY PREDICTON OF REINFOCED CONCRETE CONTAINMENT VESSELS

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ABSTRACT

Nuclear containment vessels are potentially one of the most seismically vulnerable structures. In light of the Fukushima Daiichi accident, it is becoming increasingly important to more accurately predict the ultimate capacity of containment vessels under high temperature and pressure followed by an extreme earthquake event. The improved accuracy can not only provide important data for decision makers during an unexpected nuclear accident but also provide valuable data for decommissioning reactors after an accident. The following components are studied to improve the ultimate capacity prediction: (1) The effect of high temperature on structural materials; (2) Parameters to characterize structural damage resulting from earthquake motions; (3) The effect of high temperature and pressure time history on containment failure mode; (4) The effect of thermal boundary conditions (adjoining top slab and other floors affecting containment vessel thermal behavior), not fully understood for BWR reinforced concrete containment vessels; (5) The structural behavior of reinforced concrete containment vessels differ from that of post-tensioned concrete, in that the concrete wall section is in tension while transferring the radial shear force; (6) Cracks are more likely to develop around large openings during a seismic event; and (7) other heat sources (such as heat transfer from fire at a spent fuel pool, adjacent fires and/or explosions, and convection from hydrogen gas) alter the thermal distribution. The proposed material model identifies damage parameters as a function of seismic loading history, and includes mechanistic physical behavior. This paper includes an extensive list of components and necessary experimental data that need to be included in a new material model in order to increase accuracy in ultimate capacity prediction.

INTRODUCTION

The increased accuracy in ultimate capacity prediction can be achieved by identifying seismic damage prior to a loss of ultimate heat sink. The seismic, pressure, and thermal loads are often superimposed without considering structural damage which develops over time. Significant earthquake damage to containment structures is most likely to precede a nuclear accident that accompanies increased pressure and temperature beyond the design basis and regulatory requirements (U.S. NRC, NUREG-800, 2010).

It is critical to note that performing an ultimate capacity analysis with exceedingly inaccurate stiffness may result in an overestimation of safety margins and unrealistic analysis results. A new approach has been developed to better reflect the effect of physical damage due to seismic events and a loss of coolant. The important features include material constitutive relationships and failure modes as a function of temperature.

As shown in Figure 1, the temperature in the reactor pressure vessel (RPV) during the Fukushima accident increased beyond the design basis and estimated level, which in turn underscored the importance of countermeasures to protect containment vessels from over-pressure and over-heat failure. In addition, it is critical to accurately assess the strength of containment vessels under the condition experienced during the Fukushima Diichi accident.

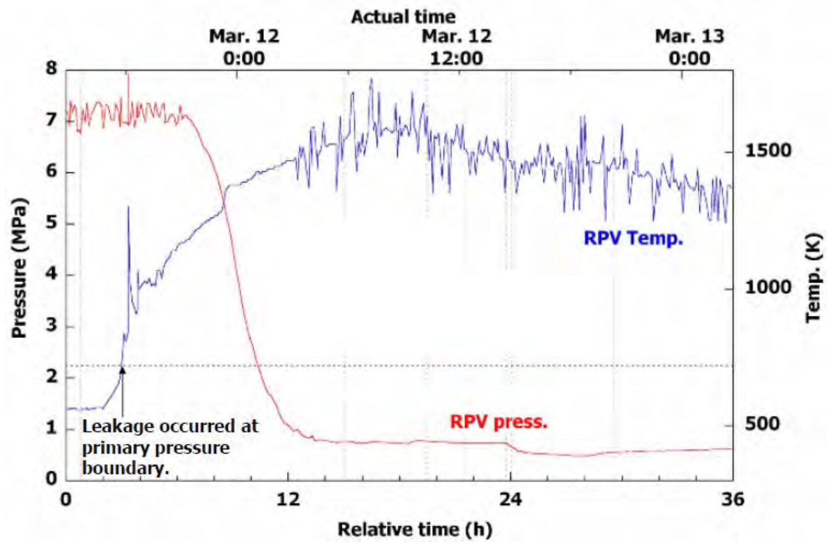


Figure 1. Pressure and Temperature History at Fukushima Unit 1 - taken from IAEA conference slides; other captions removed for clarity (Hoshi and Hirano, 2012)

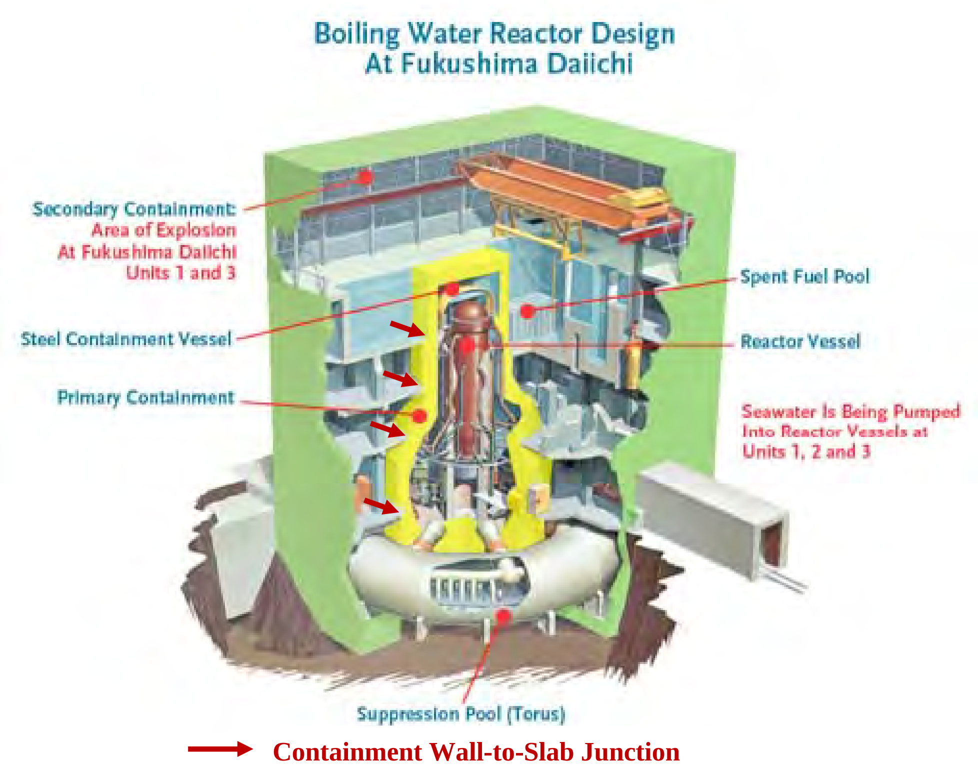


Figure 2. Typical Boiling Water Reactor Building (Institute for Energy Research, 2011).

Two (thermal and structural) physical analysis models are proposed to implement a nonlinear material model. The descriptions of two analysis models are included herein to facilitate the discussion of a nonlinear material model. The transient thermal analysis model determines the temperature distribution as a function of time using temperature dependent variables in applying conduction, convection, and radiation. In addition, the thermal boundary conditions are more accurately reflected in a proposed model. A typical Mark I type Boiling Water Reactor is enclosed in a concrete containment vessel to which the servicing floors adjoin as shown in Figure 2. Therefore, the wall-to-floor junctions are more likely to develop cracks than wall sections with uniform thickness, due to its non-uniformity and thermal massivity. The structural model needs to include improved material constitutive relationships that characterize damage parameters (e.g. in-plane shear strength reduction) as function of seismic, pressure, and thermal loading time history.

THERMAL MODEL

The transient thermal analysis model is proposed to determine a temperature profile which will be applied to a structural model. Therefore, the thermal model is geometrically identical to the structural model and includes a temperature-time history similar to one shown in Figure 1. The major features and components of the thermal model include, but are not limited to:

a. Accurate boundary conditions including reactor building slabs and walls. Non-uniform and asymmetric members, such as wall-to-slab junctions shown in Figure 2, have more complex thermal behavior. Moreover, it is more likely to develop cracks at these junctions due to local thermal massivity.
b. Inclusion of heat transfer from adjacent fires and/or an explosion.
c. Inclusion of heat transfer (conduction, convention, and fire) from a spent fuel storage pool.
d. Consideration of the rate at which heat transfers through cracks. A containment vessel develops cracks as the pressure and temperature increase. It is important to consider additional temperature increase through reinforced concrete containment wall sections due to cracks. Reinforced concrete walls that do not include pre-stressed tendons are more likely to develop cracks because of the axial (or meridional) tension resulting from internal pressure and temperature increase.
e. Consideration of heat transfer through studs embedded in concrete.
f. Reflection of heat generated from reactor base where fuel rods are inserted, in case of a core meltdown.
g. Convection from hydrogen gas buildup, if any.
h. Consideration of heat generated due to a shock wave, if any.
i. Radiation from other heat sources.
j. Dehydration of concrete shields caused by long term exposure to high temperature.

Nevertheless, the following material parameters must be developed as a function of temperature to complete the transient thermal analysis: thermal conductivity of materials (concrete, reinforcement steel, liner steel, stud), convection film coefficients, material density, and specific heat of materials (heat storage in materials).

STRUCTURAL MODEL

The structural model is geometrically identical to the 3D thermal model but includes different element types, boundary conditions, and loads. In this manner, there is no loss in interpretation of temperature data determined from the thermal model. The proposed thermal load case is different from the traditional static thermal analysis approach where one applies uniform and gradient temperature data to a structural model. Instead, the proposed structural model reads temperature data directly from the geometrically identical thermal model at selected time.

It includes the radial concrete shear strength reduction due to axial tension while considering the shear-friction mechanism. The crack strains will be determined as a function of temperature increase. In addition, the rate at which heat transfers through cracks is assessed based on the crack strains. The proposed analysis methodologies combined with a new material model is expected to better reflect the physical behavior and failure modes of reinforced concrete containment vessels.

The proposed structural model includes the following three load cases to perform a nonlinear analysis: (A) Seismic Load; (B) Thermal Load (Temperature); (C) Mechanical Load (including Impulse

Loading). A new material model is primarily developed for the three load cases. The essential components of the proposed material model are presented below.

(A) Seismic Load Case

There are a few commercially available finite element analysis programs that can analyze nonlinear concrete structures under earthquake loading; however, it is difficult to find one that is based on a mechanistic approach, an approach that reflects the true physical behavior, including shear failure and cracking during a seismic event. Moreover, it is not easy to find one that includes temperature dependent material constitutive relationships and failure modes.

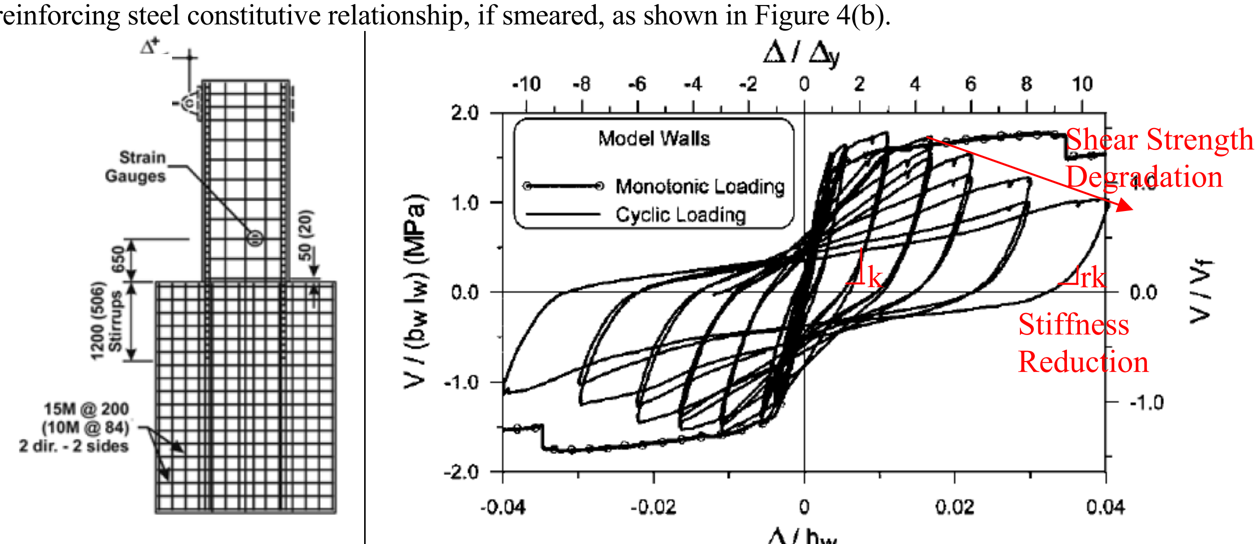
The ultimate capacity may not be accurately predicted if one simultaneously applies all three loads listed above because they do not occur concurrently. The seismic damage results from an earthquake motion over a very short duration of time. Therefore, it is important to identify the state of structural damage based on recorded earthquake motions (or ground accelerations). Then, the accident analysis (with increased temperature and pressure) can be performed with a containment structure that includes such seismic damage.

The proposed structural model includes a new material model which can characterize stiffness reduction as well as strength degradation. The following components are developed to build an improved material model.

A1 – Identification of damage parameters and stiffness reduction

The stiffness reduction due to seismic load cycles is denoted by a stiffness reduction factor, r, (Figure 3b). It is critical to identify damage parameters, such as 'r', that contribute to the stiffness reduction as well as strength degradation (Figure 3b) in each cycle based on experimental data. In case of Fukushima Daiichi, the containment vessels had been substantially damaged due to an earthquake event followed by the cooling system not performing as expected as a result of power loss.

Therefore, the extent of earthquake damage needs to be identified and reflected in the analysis model before introducing increased temperature and pressure into containment vessels. It is noted that performing an ultimate capacity analysis based on an undamaged structure may yield unsafe results. For example, at the onset of a structural analysis, the concrete material stress-strain relationship needs to start from reloading curve similar to one shown in Figure 4(a), instead of starting with the initial stiffness, E_t, when evaluating the ultimate capacity of a containment vessel. Moreover, it is worthwhile to refine the reinforcing steel constitutive relationship, if smeared, as shown in Figure 4(b).

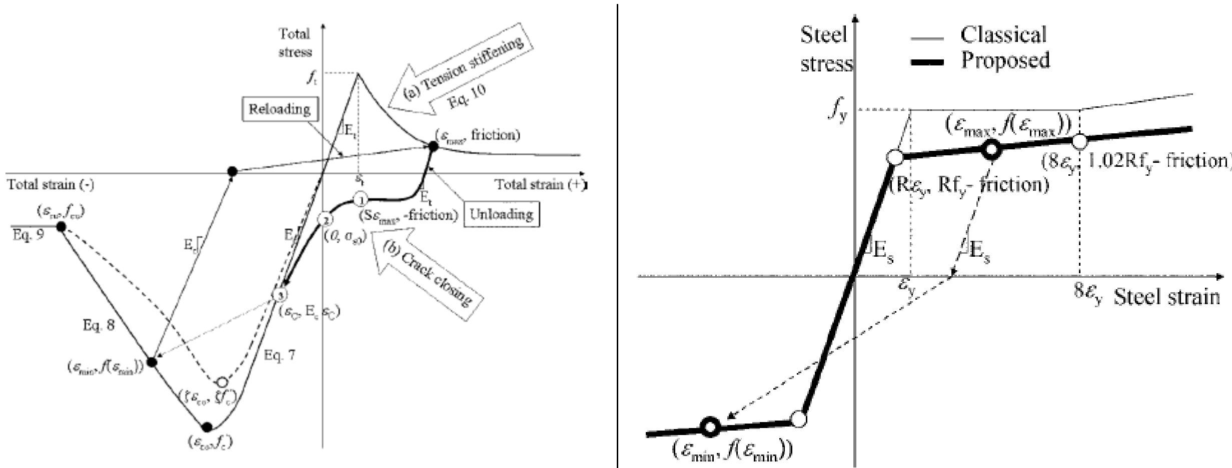


(a) Wall Specimen (b) Load-Displacement Results

Figure 3. Load-Displacement Plot (Ghorbani-Renani et al., 2009)

A2 – Biaxial stress states

The concrete material model is often represented by a uniaxial stress-strain relationship and is typically expanded to bi-axial stress states; however, the tri-axial stress states need to be incorporated in the model. There are well established concrete stress-strain relationships for the compression-compression state shown as a dashed line in Figure 4(a) and other available material models, whereas the tension-tension state has not been fully understood or established based on extensive experimental data.



(a) Concrete (b) Steel Reinforcement

Figure 4. Stress-Strain Relationship (So et al., 2010)

A3 – Characterize in-plane (or tangential) shear stress-strain relationship

It is critical to accurately evaluate shear strength degradation of containment vessels due to an earthquake. Commercially available finite element analysis programs typically adopts a linear concrete shear stress-strain relationship where the shear stress equals the elastic shear modulus times the shear strain, i.e. $\tau=G\gamma$. Once cracks develop in a concrete element, the shear modulus, G, is reduced by the shear retention factor, β, which in theory can vary between 0 and 1. This approach is problematic in that the shear retention factor is arbitrary and that the linear shear model does not limit the shear strength. The new material model needs to include a shear-friction approach that is able to limit the shear strength of crack surfaces according to the shear-friction theory so that concrete can fail in shear (Chorzepa et al., 2011). The shear strength reduction may be detrimental to integrity of containment structures and a major factor for poor ductility.

The shear-friction concept is based on the assumption that a crack will form in a plane parallel to applied shear forces and that reinforcement must be provided across the crack to resist relative displacements, i.e. separation, along the crack. When shear acts along a crack, one crack face slips relative to the other. If the crack faces are irregular and rough, this slip is accompanied by separation of the crack faces. Ultimately, the separation is sufficient to stress the reinforcement to its yield point. Thus, the reinforcement provides a clamping force equal to A_{vf} f_y (where A_{vf} is the area of shear-friction reinforcement across the interface, and f_y is the specified yield strength of shear-friction reinforcement) across the crack interface (see Figure 5). The applied shear is then resisted by friction along the crack interface, by resistance to the shearing off of protrusions on the crack interface, and by dowel action of reinforcement crossing the crack (Chorzepa et al., 2011).

The shear-friction model allows compressive stresses to develop in concrete by means of the effective strains, as the crack surfaces separate in one direction and the tensile stress develops in the reinforcing steel perpendicular to the concrete crack surfaces. Therefore, the analytical model predicts the maximum shear stress that can be obtained once the steel yields. The maximum shear stress allows concrete to fail in shear.

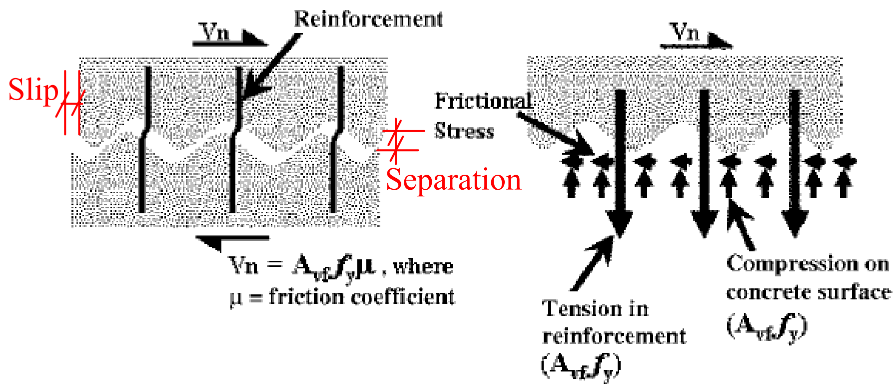


Figure 5. Shear-Friction Concept (Chorzepa et al, 2011)

In addition, there is considerable hysteretic behavior in the shear stress-strain relationship whereas existing shear models would simply be straight lines that provide unlimited shear strength as the shear strain increases and do not in any way recognize the amount of steel provided in the direction normal to the crack surface. Other shear models which include the crack slip and separation concept have been successfully implemented (Lee, 2011) in analyzing a containment vessel but are independent of reinforcement ratio.

In summary, the shear-friction approach improves the shear behavior in a uniaxial model while the two directional implementation remains challenging as cracks in the other direction may be slipping, in tension, or in compression. However, the shear model, once implemented in a 3 dimensional model, is expected to improve the physical characterization of the shear behavior (reduction in stiffness and strength) in a computational analysis model.

A4 – Identify a failure surface

A three dimensional failure surface (crushing and cracking criteria) needs to be established for seismic loading and expanded for varying temperature data for thermal loading. There are cracking criteria available in literature such as one included in Aoyagi and Yamada, 1984; however, they need to be expanded based on experimental data. Cracks are most likely to develop around large openings such as equipment hatch and personnel airlock due to earthquake motions as shown in Figure 6. The 56th IAEA conference slides (Hoshi and Hirano, 2012) suggested that there has been a pressure drop in the reactor pressure vessel due to a potential leakage at the equipment hatch or personnel airlock. It is also noted that cracking effects on seismic analysis of concrete structures are identified as one of technical issues that requires additional research during the annual Regulatory Information Conference (Xu, 2013).

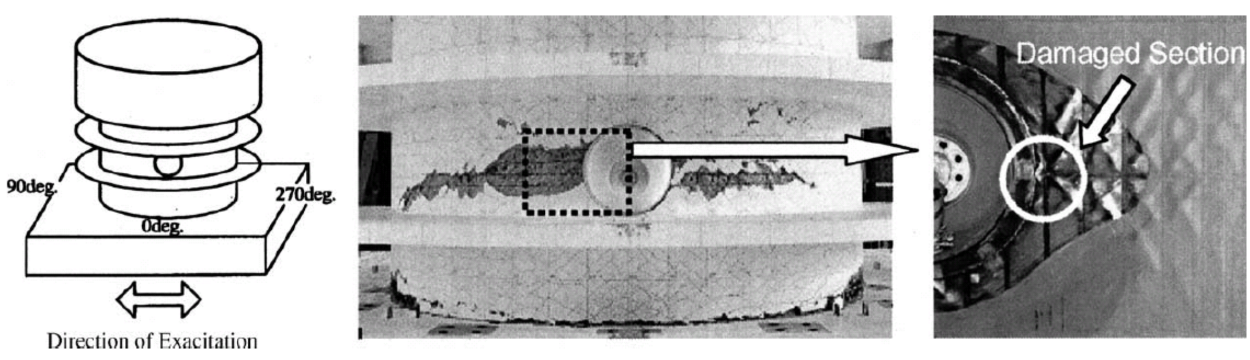


Figure 6. Containment test (1/8 scale) conducted on a shake table (Hirama et al., 2005).

(B) Thermal Load Case

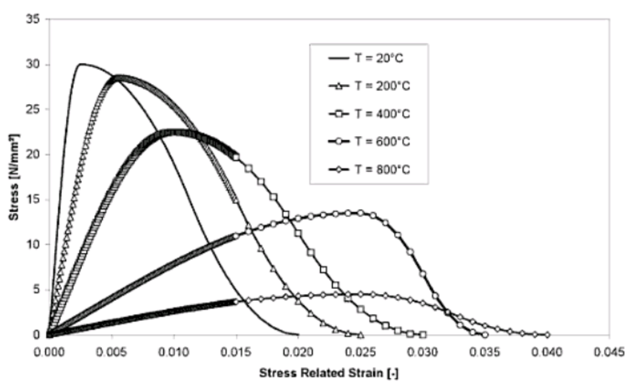
Once the earthquake damage is identified, the structural model reads temperature data directly from the thermal model at selected time and performs a nonlinear analysis. To complete a thermal analysis in a structural model, the following elements need to be considered:

B1 – Material properties as a function of temperature

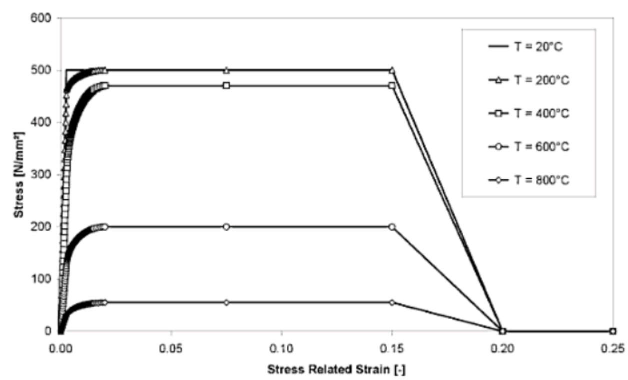
In addition to the material model characteristics identified for the seismic load case, material thermal properties available in literature (e.g. U.S. NRC NUREG/CR-7031, 2010) may be used to characterize material strength reduction in compression and tension due to temperature increase (see Figure 7). An improved stress-strain curve, particularly in the tension region, needs to be established as a function of temperature, based on the input from extensive experimental programs.

The traditional approach of applying a uniform temperature increase and a linear gradient temperature profile results in an evaluation of axial forces and moments in concrete members. However, this approach can be avoided by reading temperature distribution directly from the proposed thermal model.

The redistribution of axial forces and moments at the wall-to-slab intersections and reduction in forces due to cracking requires a nonlinear, but computationally efficient, material model. Furthermore, the effect of radial and meridional direction reinforcement ratios needs to be studied for reinforced concrete containment structures. The bond strength reduction between concrete and steel reinforcement must also be documented as a function of temperature.



(a) Concrete Compressive Stress-Strain



(b) Reinforcement Stress-Strain

Figure 7. Stress-Strain Relationship as a function of temperature (fib Bulletin No. 46, 2008).

B2 – Study radial (out-of-plane) shear force as a function of temperature.

It is fairly well understood that cracking relieves thermal moments; however, it is not thoroughly studied if the radial shear force resulting from a thermal gradient is reduced due to cracking, although the radial thermal shear force is primary (not to be reduced) per ASME code. This task is critical to assess the state of damage in containment vessels and to accurately evaluate the ultimate capacity.

In addition, the effect of radial shear reinforcement ratio on shear strength and shear strength degradation due to temperature increase needs to be investigated based on experimental data and verified with an analytical model. It is also important to recognize that radial shear force increase due to thermal loading itself does not reflect the state of damage during an accident; therefore, the shear strength reduction, if any, due to cracking under combined mechanical and thermal loading must be studied through extensive experimental programs. Furthermore, the extent of seismic damage (e.g. radial shear strength reduction) needs to be identified before this thermal study can be performed.

B3 – Characterize crushing and cracking criteria as a function of temperature.

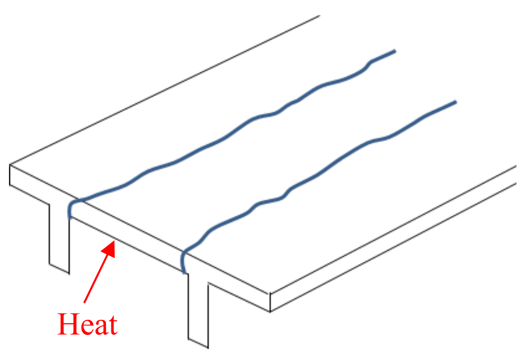
The damage surface identified for the seismic load case needs to be expanded to incorporate the effect of temperature. It is noted that available biaxial material tests had been mostly performed at room temperature, and thus the crushing, cracking, and shear failure criteria need to be expanded to include the high temperature range shown in Figure 1.

B4 – Identify crack locations and extent of cracks.

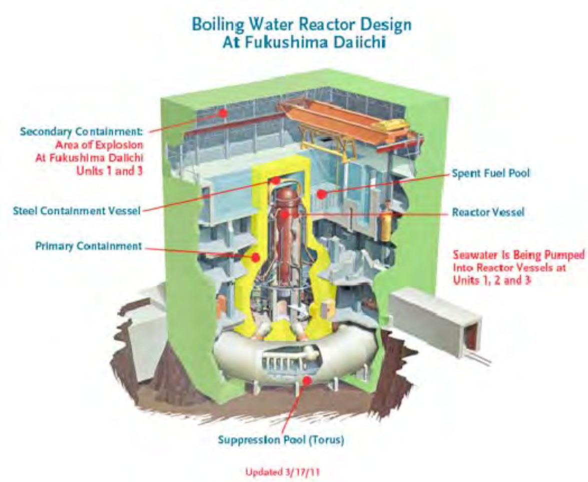
It is worthwhile to consider a fire testing of a double tee section to illustrate the importance of this task. As the double tee section heats up, cracks typically develop at the flange parallel to the stems as shown in Figure 8(a). These cracks typically result in a brittle structural failure. Similar type of cracks may develop in containment wall-to-slab junctions as they are geometrically analogous to a double tee section, although containment wall section is relatively much stiffer than the adjoining slab sections.

For example, in a reinforced concrete containment structure shown in Figure 8(b), it is likely to observe cracks at the containment wall-to-reactor building slab junctions as well as at the wall base and mid-height. However, there is limited information as to the extent of cracks and crack locations for elevated temperature. In addition, cracks developed around large openings due to an earthquake are most likely to be affected by increased temperature.

Finally, it is important to identify critical locations and the extent of cracks due to combined mechanical and thermal loading. One such serviceability requirement is the crack width which may be quantified as a function of temperature.



(a) Double Tee Section



(b) Mark I – Boiling Water Reactor (Institute for Energy Research, 2011).

Figure 8. Complex Geometry and Elevation Temperature

B5 – Study changes in geometry and lateral deflection as temperature increases.

The analytical model may not necessarily reflect geometric changes accurately due to increased temperature. The behavior of containment and reactor building under high temperature is not intuitive because of the complex geometry. It is not as simple as one for a single cylindrical tank structure with a spherical dome roof. Without an established verification process through extensive experimental programs, an analytical model can easily generate misleading results.

For instance, imagine modeling a foundation slab without assigning a temperature profile. The containment wall wants to move outwards but the foundation slab will restrain the movement. Another example lies with the servicing floors adjoining the containment walls. As the containment wall expands, there is no stress generated if it were free to move; however, it is restrained by the slabs resisting movement because the temperature of the slab is not as high as the containment wall. Therefore, the restraints from the reactor building slabs yield stresses in the containment vessel.

Furthermore, it is worthwhile to accurately measure lateral deflection and geometric changes along the height of containment wall as the pressure and temperature increase. Accurate deflection and strain measurements in reinforcement at multiple locations through the thickness of wall can be used to verify the proposed material model given that available sensor technology (e.g. fiber optics) can support such high temperature environment.

It is also strongly encouraged to develop experimental programs which include a significant portion of adjoining slabs and a base mat foundation in order to accurately reflect the behavior of containment vessels under high temperature. Another challenge lies with areas around large openings and their behavior under increased temperature beyond the design basis.

B6– Study the effect of liner and studs

The effect of liner expansion on a concrete containment vessel needs to be evaluated. In addition, increased concrete temperature due to a heat transfer through studs embedded in concrete should be quantified through an experimental program.

(C) Mechanical Load Case – High Pressure and other loads

C1 - Capture any changes in internal pressure

The internal pressure increases during an accident. However, the internal pressure can drop from opening of a relief value or drywall head lift, while temperature may continue to increase as shown in Figure 1 and remain elevated for several months. Therefore, the effect of pressure history, loading and unloading, needs to be investigated in conjunction with the temperature-time history.

C2 - Consider other mechanical loads

One of the lessons learned from the Fukushima accident is the fact that impulse loads due to an explosion or a detonation shock wave and its effect on containment structures may need to be studied in addition to the design basis loads.

OTHER RECOMMENDATIONS

This paper provides necessary ingredients to perform a real-time simulation of accident scenarios. That is, the thermal and structural analysis models may be used to perform an integrity evaluation, as soon as the recorded earthquake ground motion data is available to identify the structural damage due to a seismic event. Then, the structural model that includes seismic damage will continue to run with temperature results from a transient thermal analysis, as recorded temperature and pressure inside of a containment vessel becomes available. The proposed mechanistic material model based on reliable experimental results will enable an assessment of the structural damage due to increased temperature and pressure.

Furthermore, the material model will enable a sensitivity analysis that needs to be performed to study the damage parameters and to quantify the risk of earthquakes and/or high temperature/pressure beyond design basis events, attributing to an ultimate containment failure.

CONCLUSION

This paper includes an extensive list of necessary components and required experimental programs to enable a new material model and increase accuracy in ultimate capacity prediction. The most critical and urgent task is to develop a mechanistic material model that can accurately characterize seismic damage of containment structures. The damage parameters include stiffness reduction in each cycle as well as shear strength reduction. While the seismic model needs to be verified with experimental data, a temperature-dependent material model, which includes material strength degradation due to increased temperature, concrete cracking, and bond-slip needs to be further investigated, in conjunction with the pressure time history.

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