Committee 376
Concrete Structures for RLG Containment

Agenda ACI 376-C
Analysis Sub-Committee Meeting,
Sunday, March 23, 2014, 3 PM – 5 PM
Grand Sierra Resort,
Reno, NV
Room: N-12

1. CALL TO ORDER and APPROVAL OF AGENDA
2. INTRODUCTIONS
3. ANNOUNCEMENTS
4. DISCUSSION: TN on Design and Analysis of the TCP Embedment Zone
   • Resolution of remaining negative votes and comments.
5. OTHER BUSINESS / INFORMAL DISCUSSION OF PROJECTS
6. ADJOURNMENT
### Technical Note on TCP (TCP – TN)

**Approved Sections**

- Section Approved with Comments to be resolved
- Negative Vote
  - 2013.04.13 376-C Minneapolis
  - 2014.02.14 376-Webinar

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### Members that Voted

<table>
<thead>
<tr>
<th>Voting Members that voted (79%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. Hoptay, Joseph</td>
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<tr>
<td>10. Howe, Thomas R</td>
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<tr>
<td>11. Jiang, Daju</td>
</tr>
<tr>
<td>12. Khalifa, Jameel U</td>
</tr>
<tr>
<td>13. Kristulovic-Opara, Neven</td>
</tr>
<tr>
<td>14. Legatos, Nicholas A</td>
</tr>
<tr>
<td>15. Malhotra, Praveen</td>
</tr>
<tr>
<td>16. Mash, Keith</td>
</tr>
<tr>
<td>17. Moncarz, Piotr D</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Associate Members</th>
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<tbody>
<tr>
<td>• Roetzer, Josef</td>
</tr>
<tr>
<td>• Widianto, Widianto</td>
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<table>
<thead>
<tr>
<th>Members that did not vote</th>
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</thead>
<tbody>
<tr>
<td>23. Hanskat, Charles S</td>
</tr>
<tr>
<td>24. Douglas, Hamish</td>
</tr>
<tr>
<td>25. Hashmi, Humayun</td>
</tr>
<tr>
<td>26. Rajan, Ramanujam S</td>
</tr>
<tr>
<td>27. Sward, Robert</td>
</tr>
<tr>
<td>28. Thompson, Eric</td>
</tr>
</tbody>
</table>

### Members Attending:

1. Brannan, Mike
2. Hjorteset, Kare
3. Ballard, Thomas A
4. Allen, Junius
5. Garrison, Jeffrey
6. Hoff, George C
7. Hoff, George C
8. Hoptay, Joseph
9. Howe, Thomas
10. Khalifa, Jameel
11. Pawski, Rolf
12. Hanskat, Charles
13. Roetzer, Josef

### Participating:

1. Allen, Junius
2. Brannan, Mike
3. Douglas, Hamish
4. Garrison, Jeffrey
5. Hoptay, Joseph
6. Hoff, George C
7. Howe, Thomas
8. Jiang, Daju
9. Legatos, Nick
10. Kristulovic-Opara, Neven
11. Mash, Keith
12. Mehta, Sanjay
13. Oliver, Billy
14. Pawski, Rolf
15. Roetzer, Josef
16. Vossoughi, Fariborz

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### 1st Ballot Results (Approved w. Comment)

<table>
<thead>
<tr>
<th>Ref No.</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I am not sure the TCP can be constructed as detailed because it would be impossible to weld both sides of the TCP plate to the embedment plate. It would also be better to radius the sharp corner shown on the TCP plate. Would it be possible to simply lap weld the TCP plate to the embedment plate? Should the embedment zone also extend 2X the wall thickness below the embedment plate?</td>
<td>Brannan</td>
<td></td>
</tr>
</tbody>
</table>

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### 2nd Ballot Results

**Suggested Change**

- Agree - Jiang, Moncarz, Hoff, Khalifa, Rushing, Humayun, Howe, Wu, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Kristulovic
- Agree with comment - Hoffman

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### 2nd Ballot: Response being BALLOTED

- The comment found partially persuasive. It is not intended that the TN covers TCP construction details. Furthermore, welding requirements should be as per API 620. Address the comment by revising text on pages 11-14:

  **INTRODUCTION**

  ACI 376 provides requirements and some basic recommendations for the design of the Thermal Corner Protection (TCP) embedment zone. The purpose of this technical note document is to provide further guidance on (a) design and analysis of the TCP embedment anchors, detailing and (b) liquid-tightness analysis for crack width calculations in the TCP embedment zone (i.e., Crack width calculations).
## 1st Ballot Results (Approved w. Comments)

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<tr>
<td>8</td>
<td>Suggest rewording and removing ‘substantially’ link to definitive acceptance criterion to avoid confusion. Suggest exact acceptance criterion words such as - under the spillage condition the crack widths on the inside face shall be limited to xx, compressive stresses in both the meridional and vertical directions shall be minimum y, max z, &quot;The concrete wall above the TCP, directly exposed to spilled product, should remain liquid and substantially vapor tight during the spill condition. This is assured by maintaining a compression zone in the wall exposed to the spill and by limiting the crack width cracking on the inside face of the wall in the vicinity of the TCP embedment plate zone during a spill. &quot;</td>
<td>Mash</td>
<td>The comment found partially persuasive. Limiting values are covered in the Code (e.g., compressive zone size, crack width limits, etc.) and do not need to be repeated here. Revise text for clarity to read: &quot;The concrete wall above the TCP, directly exposed to spilled product, should remain liquid tight and substantially vapor tight during the spill condition. This is assured by maintaining a compression zone in the wall exposed to the spill and by limiting the crack width cracking on the inside face of the wall in the vicinity of the TCP embedment plate zone during a spill. &quot;</td>
</tr>
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## 2nd Ballot Results

### Voting Member’s VOTE & COMMENTS

<table>
<thead>
<tr>
<th>Suggested Change</th>
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<tbody>
<tr>
<td>I have no objection to the proposed changes</td>
</tr>
<tr>
<td>I believe the embedment zone should extend at least to the bottom of the TCP plate since migration of cracks in this zone would compromise the leak tightness of the detail.</td>
</tr>
<tr>
<td>2014.02.14 Webinar Ballard wording ok</td>
</tr>
</tbody>
</table>

### 2013.04.13 – 376-C Minneapolis:

| Agree with editorial changes – Khalifa, Roetzer, Krstulovic |

### 2014.02.14 Webinar Ballard wording ok

| Agree with editorial changes – Khalifa, Roetzer, Krstulovic |

### 2013.04.13 – 376-C Minneapolis:

| Agree and that Tom Ballard to propose wording. From TB email dated 2013.04.15: “Although the code and this TN do not explicitly define leak tightness criteria for the anchorage and embedment, the design and construction of these components should be carried out with the clear objective of protecting the corner joint from product temperatures.” |

### 2013.04.14 – 376-D webinar

| Ballard wording ok |

### 2014.02.14 Webinar Ballard wording ok

| Agree with editorial changes – Khalifa, Roetzer, Krstulovic |

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**Update title to read:**

Thermal Corner Protection Design & Crack Analysis

Design and Analysis of the TCP Embedment Zone
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<tbody>
<tr>
<td>11</td>
<td>Page 5, line 4, item 6</td>
<td>Mash</td>
<td>Assurance is through cracks + compression zones not through cracks alone. Crack width limitation in the vicinity of the embed is to prevent liquid migration behind the TCP area. No action. Covered in previous response.</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>P. 5, Line 15</td>
<td>Wu</td>
<td>Add &quot;seismic Aftershock load&quot;.</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Page 5, line 21, item 10</td>
<td>Mash</td>
<td>Starting temperatures and conditions should be selected so as to maximise the demand under consideration. For instance for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking to the embed. Whereby creating maximum straining across the section. The comment found persuasive. Add proposed text to line 22: 1.2.1 – STEP 1: TCP Load Definition Finite element analyses is performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment will be subjected to including thermal, prestress, creep, concrete shrinkage, internal</td>
<td></td>
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### 2nd Ballot Results

#### RESPONSE being BALLOTED

- Pressure, hydrostatic pressure and hydrodynamic pressure due to seismic aftershock.
- Starting temperatures and conditions should be selected so as to maximize the demand under consideration. For instance for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking to the embed. Whereby creating maximum straining across the section.

#### Voting Member's VOTE & COMMENTS

- Agree with editorial changes - Hoff
  - For instance, for the design of the anchors, the critical condition is likely to be a warm wall (summer) and with a cold shocking to the embedment, thereby creating maximum straining across the section.

- Agree with minor comment - Humayum
  - last sentence - straining or strain?

- Agree with minor comment - Brannan
  - consider using “Design” instead of “Starting”.

- Agree with editorial changes - Pawski
  - Starting temperatures and conditions should be selected so as to maximize the demand under consideration. For instance for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking thermal shock to the embed. Whereby creating maximum straining across the section.

- Agree with editorial changes - Douglas
  - This is addressed by 376-C Minneapolis response above.

- Agree with changes - Allen
  - For instance for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking to the embed. Whereby creating maximum straining across the section.

- Agree with changes - Oliver
  - Agree with suggested grammatical revision.

| 16 | P. 5, Line 22, at the end of the paragraph | Add “and hydrodynamic pressure due to seismic aftershock.” Wu |
|    | The comment found persuasive. Change text to read: | The comment found persuasive. Change text to read: |
|    | Finite element analyses is performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment | Finite element analyses is performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment |
### 1st Ballot Results (Approved w. Comment)

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<tr>
<td>18</td>
<td>Page 5, line 28, item 12</td>
<td>Suggest inclusion of the words 'in the absence of a defined leak rate all intermediate levels shall be investigated. In practice this may be achieved by running a number spill levels to so as adequately bound the demands. Typically 5 levels may be used dividing the spill height into 4 equal units. In addition levels in close proximity to the TCP must be investigated.</td>
<td>Agree in principle with comment. Revise as noted and address spill levels in a future edition of the Code.</td>
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### 2nd Ballot Results

**2ND BALLOT:** RESPONSE being BALLOTED

**Voting Member's VOTE & COMMENTS**

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<td>Agree in principle with comment. Revise as noted and address spill levels in a future edition of the Code.</td>
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**Suggested Change**

- **Will be subjected to including thermal, prestress, creep, concrete shrinkage, internal pressure, hydrostatic pressure and hydrodynamic pressure due to seismic aftershock SSEAFt.**

  - **Widianto, Hoptay, Oliver, Pawski, Hatfield, Brannan, Krstulovic**

  - Agree with editorial change – Khalifa, Douglas, Roetzer, Krstulovic

  - "Finite element analyses are performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall."

- **Various spill levels should be considered to determine the most severe effect on the embedment and concrete wall. This should include a spill level located not below the top of the TCP which will place the largest temperature differential between the TCP and the concrete wall, as well as a minimum of three levels should be considered for spill levels above the TCP up to, at top of the TCP embedment zone, at mid-height, and full spill height.**

  - **Agree – Jiang, Moncarz, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Allen, Legatos, Widianto, Roetzer, Hatfield, Brannan, Krstulovic**

  - **Agree with suggested change - Khalifa**

  - **Agree with editorial changes – Hoff, Pawski**

  - **Agree with editorial changes - Douglas**

  - **Agree with editorial comment - Oliver**

- ** “…at the top of the TCP embedment zone, at mid-height, and full spill height”**

  - **Disagree - Mash**

  - Statement of 3 levels does not reflect the significance of the analysis. This is the most important analysis carried out for the outer tank and it is essential that an appropriate amount of levels be considered.

  - Suggest that the text is amended to the following:

  - **Also a minimum of five levels should be considered.**

  - **2013.04.13 – 376-C Minneapolis:**

  - Mash comment non-persuasive. Three is a minimum and does not preclude specifier from requiring or the designer choosing more.

  - **Agree with suggested change - Khalifa**

  - **Agree with editorial changes - Douglas**

  - **Agree with editorial changes - Hoptay**

  - **Agree with editorial changes – Hoff, Pawski**

  - **Agree with editorial changes - Douglas**

  - **Agree with editorial comment - Oliver**

  - **Agree with suggested change - Khalifa**

- **…”at the top of the TCP embedment zone, at mid-height, and full spill height”**

  - **Disagree - Mash**

  - Statement of 3 levels does not reflect the significance of the analysis. This is the most important analysis carried out for the outer tank and it is essential that an appropriate amount of levels be considered.

  - Suggest that the text is amended to the following:

  - **Also a minimum of five levels should be considered.**

- **2014.02.14 Webinar**

  - Discuss in Reno the issue of safety. Mash insists 5 minimum is a good starting point and contractor must demonstrate they have identified critical
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<tbody>
<tr>
<td>20</td>
<td>Page 5, line 32, item 14</td>
<td>Must be achieved through mechanical anchoring!</td>
<td>The comment found persuasive. Revise to read: “The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall by other suitable means (e.g., embedment plate should be placed in continuous (circumferential) rows along the concrete wall.”</td>
</tr>
<tr>
<td>21</td>
<td>Page 6, line 1, item 1</td>
<td>When? Embedment must be anchored with studs?</td>
<td>The comment found persuasive. Revise to read as noted below: Address questions on spacing and gap size in future. “When the TCP embedment plate is should be anchored with circumferential studs, a minimum of two rows of circumferential studs should be used to anchor the embedment plate. The spacing between mechanical anchors (studs) has significant impact on the TCP embedment.</td>
</tr>
</tbody>
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### 1st Ballot Results (Approved w. Comment)

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### 2nd Ballot Results

**2ND BALLOT: RESPONSE being BALLOTED**

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<tr>
<td></td>
<td>The comment found non-persuasive regarding suggested inclusion of bar detailing because this is normal everyday concrete detailing. Add the following after line 7 on page 6.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>• “Anchor spacings should be selected to as to be multiples of the bar spacing to enable a clash free design.”</td>
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<td></td>
<td>Delete lines 6 and 7 on page 6.</td>
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<td></td>
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<td></td>
<td>• “Allowable stresses i.e., material selection and material requirements used in the design of the embedment plates, may be selected in accordance with 412.5.0.”</td>
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<td></td>
<td>The embedment plate should be anchored with a minimum of two circumferential rows of anchors. The spacing between anchors has significant impact on the TCP embedment performance and thus should be considered in the design.</td>
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<td></td>
<td>“Anchors” to be used throughout. Edit TN and replace bolts &amp; studs with “anchors.”</td>
<td></td>
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**Voting Member’s VOTE & COMMENTS**

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<tr>
<td></td>
<td>Agree with comments - Pawski</td>
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<td></td>
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<tr>
<td></td>
<td>Bullet points 1 &amp; 2 should be combined</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Use “studs” or “bolt studs” consistently</td>
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<tr>
<td></td>
<td>Note that our Figure 1.1a shows four rows of circumferential studs. Should it show two rows of studs in solid line ink and the other two in shaded or dashed ink to indicate the potential for using more than two rows?</td>
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**Suggested Change**

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<tr>
<td></td>
<td>Agree, annotate sketch to state “2-rows minimum.”.</td>
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<tr>
<td></td>
<td>Also recommend deleting bolts from first line under section 1.2.3</td>
<td></td>
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**Disagree - Hoptay**

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<tr>
<td></td>
<td>Studs are not always used for consistency suggest the following rewording</td>
<td></td>
<td></td>
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The embedment plate should be anchored with a minimum of two circumferential rows of anchors. The spacing between anchors has significant impact on the TCP embedment performance and thus should be considered in the design.

 **2013.04.13 – 376-C Minneapolis:**

Agree – Jiang, Moncarz, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Hoff, Hoptay, Malhotha, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic
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<tbody>
<tr>
<td>NEW</td>
<td>Page 6 Para 1.2.4</td>
<td>This comment inserted by Pawski 2013.04.23</td>
<td>This comment inserted by Pawski 2013.04.23.</td>
</tr>
<tr>
<td>28</td>
<td>Page 7, line 14, item 1</td>
<td>Mash</td>
<td>Suggest using nomenclature such as demand as opposed to load.</td>
</tr>
<tr>
<td>32</td>
<td>Page 7, line 20, item 6</td>
<td>Mash</td>
<td>EN only calculates characteristic widths. Historically US codes have cocooned the crack width requirements into the detailing rules. These were based on the Gergely Lutz expressions which used mean widths. Replace ‘as per’ with ‘in accordance with’</td>
</tr>
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**2nd BALLOT: RESPONSE being BALLOTED**

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<tbody>
<tr>
<td>Douglas additional comment 2 at end of Ballot Summary:</td>
<td>Douglas</td>
</tr>
<tr>
<td>The liquid tightness criteria are specified</td>
<td>The liquid tightness criteria are specified in Para 2.1, items 1 &amp; 2. Additional tightness criteria on “embedment plates” should not require to be defined by owner. I am not in favour of definitions to be provided by owners. The statement is vague and ultimately provides no guidance. The code is to provide guidance to all, including owners.</td>
</tr>
<tr>
<td><strong>NEW BUSINESS for CODE - JG write the new business item on code change form Q1.</strong></td>
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**NEW BUSINESS for CODE - JG write the new business item on code change form Q1.**

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<tr>
<td>Disagree - Hoptay</td>
<td>Withdrawn.</td>
</tr>
<tr>
<td>Suggest rewording sentence as follows to cover both the transient and steady state condition.</td>
<td><strong>The integrity of the concrete wall must be maintained during the entire spill.</strong></td>
</tr>
<tr>
<td>Suggest that: a) EN 1992-1-1 should stay, as stated in ACI 376 to delete “as characteristic and not mean”</td>
<td><strong>The integrity of the concrete wall must be maintained during the entire spill.</strong></td>
</tr>
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**2013.04.13 – 376-C Minneapolis:**

**Discussed and agree with comment.**

**2013.04.13 – 376-C Minneapolis:**

**Withdrawn.**
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<th>Text</th>
<th>Author</th>
<th>Comments</th>
<th>2ND BALLOT: RESPONSE being BALLOTED</th>
<th>Voting Member's VOTE &amp; COMMENTS</th>
<th>Suggested Change</th>
</tr>
</thead>
</table>
| 34     | Section 2.2.1 Page 7, Line #31 1) Modeling  
2) Modeling including modeling geometry and material thermal properties | Jiang | Suggest to change to:  
1) Modeling including modeling geometry and material thermal properties  
2) "Modeling including specific tank geometry and material thermal properties" | The comment found persuasive. Revise page 7 lines 20-21 to read:  
1) "Modeling including specific tank geometry and material thermal properties" | | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Mallhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hopitay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic |
|        | 2013.04.13 – 376-C Minneapolis:  
Persuasive since crack widths calculated by EN 1992-1-1 will be characteristic. Proposed wording to be adopted. | | | | | |
<p>|        | Disagree - Garrison | | | b) Committee needs to review the ability of the contractor/designer to meet the requirement of 0.008&quot; max crack width using EN equations for the spill condition (2 cryogenic temperatures). Experience shows that this is a difficult requirement to meet. Instead, perhaps ACI 376 should specify minimum rebar size and spacing within the TCP embedment zone. | | |
|        | Disagree - Mash | | | By removing the design code there is potential for use of codes that do not generate characteristic levels. In particular Model Code 90 is not prohibited, also Ven der Veen’s approach generates mean expectation of crack widths. There are some Contractors still purporting to MC90 and reviewer has a concern this will continue if left unchecked. Without guidance the Client is without a Captain and I uninformed. Note the NL Analysis is in accordance with EN so there should be no objection to using EN for crack widths. | | |
|        | 2014.02.14 Webinar | | | Mash ok as long as Characteristic is the basis. Discuss Wu comment in Reno concerning reference to EN 1992-1-1. Webinar consensus was to include reference to EN 1992-1-1 for clarity. | | |</p>
<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Text</th>
<th>Author</th>
<th>Comments</th>
<th>Suggested Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>steady state final</td>
<td></td>
<td>4)  &quot;Continue analysis until steady state final temperatures are reached</td>
<td>Committee needs to define analysis / design requirements.</td>
</tr>
<tr>
<td></td>
<td>temperatures are reached and</td>
<td></td>
<td>and the temperature distribution is obtained</td>
<td>Considering the variability in the possible loading conditions, variability in</td>
</tr>
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<td></td>
<td>the temperature distribution</td>
<td></td>
<td></td>
<td>material properties and variability in modeling techniques it seems that a steady</td>
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<tr>
<td></td>
<td>is obtained</td>
<td></td>
<td></td>
<td>state analysis would be sufficient.</td>
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<td>2014.02.14 Webinar</td>
</tr>
<tr>
<td></td>
<td>and any other steady state</td>
<td></td>
<td>3) &quot;To establish initial conditions, apply dead load, prestressing,</td>
<td>Committee needs to define analysis / design requirements.</td>
</tr>
<tr>
<td></td>
<td>load, iterate to equilibrium&quot;</td>
<td></td>
<td>thermal operating thermal and any other steady state load, then iterate to</td>
<td>Considering the variability in the possible loading conditions, variability in</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>equilibrium&quot;</td>
<td>material properties and variability in modeling techniques it seems that a steady</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>state analysis would be sufficient.</td>
</tr>
<tr>
<td>44</td>
<td>Determine strains in section,</td>
<td>Mash</td>
<td>The comment found persuasive. Change text to read:</td>
<td>Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic.</td>
</tr>
<tr>
<td></td>
<td>check for Residual</td>
<td></td>
<td>5) Beginning with the initial condition defined in step 2, compute crack</td>
<td>'2014.02.14 Webinar</td>
</tr>
<tr>
<td></td>
<td>Compressive Zone (RCZ),</td>
<td></td>
<td>widths at time steps where reinforcing strains are the greatest, and</td>
<td>Mash delete &quot;then iterate to equilibrium&quot; is not losing anything</td>
</tr>
<tr>
<td></td>
<td>check for max comp stress</td>
<td></td>
<td>exceed the material yield stress. Furthermore, at each time step</td>
<td>Pg 8 line 11 &amp; 13 delete as suggested.</td>
</tr>
<tr>
<td></td>
<td>etc.</td>
<td></td>
<td>determine the adequacy of the compression zone.&quot;</td>
<td></td>
</tr>
<tr>
<td>Ref No.</td>
<td>Text</td>
<td>Author</td>
<td>Comments</td>
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<tr>
<td>47</td>
<td>Section 2.2.2&lt;br&gt;Page 8, Line # 11&lt;br&gt;5) Computer crack widths at times throughout the transient where reinforcing strains are the greatest and the stresses exceed the material yield stress</td>
<td>Jiang</td>
<td>Suggest to change to:&lt;br&gt;6) Computer crack widths at times throughout the transient where reinforcing strains are the greatest and the stresses exceed the material yield stress</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Page 8, line 18, item 7</td>
<td>Mash</td>
<td>What does this mean?</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Section 2.3.1&lt;br&gt;Page 8, Lines # 21 to 23&lt;br&gt;&quot;In this case a non-linear finite element program is used in conjunction with&lt;br&gt;Non-linear FE material constitutive models for...&quot;</td>
<td>Jiang</td>
<td>Suggest to change to:&lt;br&gt;&quot;In this case a non-linear finite element program is used by:&lt;br&gt;Non-linear FE material constitutive relationship for concrete and steel&lt;br&gt;Carrying out FE analysis to obtain stress/strain contours, and&lt;br&gt;Performing FE analysis post process to calculate crack width as per Eurocode 2 1992-1-1&quot;</td>
<td></td>
</tr>
</tbody>
</table>
### 1st Ballot Results (Approved w. Comment)

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Text</th>
<th>Author</th>
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<tbody>
<tr>
<td></td>
<td>concrete and steel, and Crack width calculations as per E</td>
<td></td>
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</tbody>
</table>

### 2nd Ballot Results

#### 2ND BALLOT: RESPONSE being BALLOTED

- Performing FE analysis post-process to calculate characteristic crack width, calculations following a method, such as Eurocode 2 EN 1992-1-1 (see section 2.5 in this TN).

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Suggested Change</th>
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<tbody>
<tr>
<td></td>
<td>Agree with minor changes - Khalifa</td>
</tr>
<tr>
<td></td>
<td>Agree with minor changes - Ballard</td>
</tr>
<tr>
<td></td>
<td>Agree with changes - Widianto</td>
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<tbody>
<tr>
<td></td>
<td>To be consistent with Sections 2.3.1 and 2.3.2, suggest the sentence is re-worded as follows:</td>
</tr>
<tr>
<td></td>
<td>&quot;Non-linear or simplified finite element (FE) analysis should be used as discussed in 2.3.1 and 2.3.2.&quot;</td>
</tr>
<tr>
<td></td>
<td>To be consistent with the last sentence in Section 2.3, I suggest that we switch the order between the current Sections 2.3.1 and 2.3.2 (i.e., present Simplified FE analysis in Section 2.3.1 and present non-linear FE analysis in Section 2.3.2). This will also be consistent with the progression of the actual design, where Simplified FE analysis is done in the preliminary design, before non-linear FE analysis.</td>
</tr>
</tbody>
</table>

---

### 53

**Section 2.3.2**

Page 9, Lines # 2 & 3

"However, it should be noted that this is a very time consuming process and is thus usually used in the preliminary design."

Jiang

Suggest to change to:

"However, it should be noted that this is a very time consuming process and is thus usually used for focusing on more critical load cases after a preliminary screen for load cases has been performed in the preliminary design."

Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic

---

The comment found persuasive. Remove the whole sentence.

"However, it should be noted that this is a very time consuming process and is thus usually used for focusing on more critical load cases after a preliminary screen for load cases has been performed in the preliminary design."
## 1st Ballot Results (Approved w. Comment)

<table>
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<tr>
<th>Ref No.</th>
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<th>Author</th>
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</table>
| 56      | Section 2.3.2 Page 9, Lines # 4 & 5 “Moment-Curvature Approach: The moment curvature response is obtained using a concrete section analysis program in conjunction with.” | Jiang | Suggest to change to: “Moment-Curvature Approach: The moment curvature response is obtained using a concrete section analysis program by implementing.” The comment found persuasive. Change text to read: 2.3.2 **Simplified Linear FE Analysis** Simplified Linear FE analysis is usually used only in the preliminary design.  
**Comment:** Weather should this approach be considered as "Linear Analysis" or "Non-linear Analysis"? May be this approach could be considered as a simplified non-linear analysis approach and should be used for preliminary only.  
- non-linear stress-strain material properties, and  
- a non-linear shell formulation that accounts for the cracking induced stiffness redistribution.  
This moment-curvature approach would only be suitable for consideration of the steady state linear thermal gradients and should also be used only for preliminary design. |

| 63      | Page 9, line 34, item 4  
2014.02.14 Webinar Oliver withdraw negative to editorial RP review if moving to another location | Mash | Seems out of place in terms of the flow of the document. The comment found persuasive. Edit text as shown below:  
"2.3.4 Loading  
The RLG spill case should ……..”  
Nodal temperature transients will typically be computed in a separate heat transfer finite element or finite difference solution. The thermal model used for determining nodal temperatures is also a high density model which should include concrete foundation, soil thermal boundary condition, walls, roof and outside or inside ambient temperature boundary conditions. This model should also include the base slab insulation and the thermal corner protection insulation.” |

| 66 A    | Page 10 Line 10  
On the code side of ACI 376 ASTM A706 is not referred to as low temperature reinforcing, only in the commentary. Can it be referred to as low temperature reinforcing in the technical note? | Hoptay | The comment found persuasive. Change text to read:  
"The concrete wall internal temperatures from the thermal model are also typically used for selection and documentation of reinforcement for regular concrete walls (A206) and reinforced reinforcing complying with the requirements of ACI 376.” Furthermore, in a future Coed revision, revisit the use of A706 materials in ACI 376 section 4.7.2. |

## 2nd Ballot Results

### 2ND BALLOT: RESPONSE being BALLOTED

<table>
<thead>
<tr>
<th>Ref No.</th>
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<th>Author</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 63      | Page 9, line 34, item 4  
2014.02.14 Webinar Oliver withdraw negative to editorial RP review if moving to another location | Mash | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Pawski, Hatfield, Brannan, Krstulovic  
This response does not address the basic comment that this whole paragraph doesn’t belong under “Loading”. Suggest moving it to Section 2.3.3 “Mesh Type and Size”, or inserting a new section before “Loading” called “Thermal Model”. |
| 66 A    | Page 10 Line 10  
On the code side of ACI 376 ASTM A706 is not referred to as low temperature reinforcing, only in the commentary. Can it be referred to as low temperature reinforcing in the technical note? | Hoptay | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic |

### Voting Member’s VOTE & COMMENTS

<table>
<thead>
<tr>
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<th>Author</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>Section 2.3.2 Page 9, Lines # 4 &amp; 5 “Moment-Curvature Approach: The moment curvature response is obtained using a concrete section analysis program in conjunction with.”</td>
<td>Jiang</td>
<td>Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
</tr>
</tbody>
</table>
| 63      | Page 9, line 34, item 4  
2014.02.14 Webinar Oliver withdraw negative to editorial RP review if moving to another location | Mash | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Pawski, Hatfield, Brannan, Krstulovic  
This response does not address the basic comment that this whole paragraph doesn’t belong under “Loading”. Suggest moving it to Section 2.3.3 “Mesh Type and Size”, or inserting a new section before “Loading” called “Thermal Model”. |
| 66 A    | Page 10 Line 10  
On the code side of ACI 376 ASTM A706 is not referred to as low temperature reinforcing, only in the commentary. Can it be referred to as low temperature reinforcing in the technical note? | Hoptay | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic |

### Suggested Change

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<tr>
<td>56</td>
<td>Section 2.3.2 Page 9, Lines # 4 &amp; 5 “Moment-Curvature Approach: The moment curvature response is obtained using a concrete section analysis program in conjunction with.”</td>
<td>Jiang</td>
<td>Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
</tr>
</tbody>
</table>
| 63      | Page 9, line 34, item 4  
2014.02.14 Webinar Oliver withdraw negative to editorial RP review if moving to another location | Mash | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Pawski, Hatfield, Brannan, Krstulovic  
This response does not address the basic comment that this whole paragraph doesn’t belong under “Loading”. Suggest moving it to Section 2.3.3 “Mesh Type and Size”, or inserting a new section before “Loading” called “Thermal Model”. |
| 66 A    | Page 10 Line 10  
On the code side of ACI 376 ASTM A706 is not referred to as low temperature reinforcing, only in the commentary. Can it be referred to as low temperature reinforcing in the technical note? | Hoptay | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic |
### 1st Ballot Results (Approved w. Comment)

<table>
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<th>Ref No.</th>
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<th>Author</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 74      | 1) Code and TN need to define conditions for transient thermal analysis for the spill condition (leak rate).  


2) Update and change the model to the latest 2004 edition of the Eurocode. |

- The comment found partially persuasive.  
  - 1) Definition of the spill loading is beyond the scope of the current TN and will thus be addressed in a separate document defining LNG spill conditions.  
  - 2) Update and change the model to the latest 2004 edition of the Eurocode. |

| 75      | Appendix A Pages 15-16 | Pawski | 1) It is redundant because it repeats paragraphs 2 through 4 in section 2.1 (page 7, lines 9-21) |

- The comment found non-persuasive. The comment found to be an editorial comment. Appendix A is a “copy” of what is in the Code. It is provided for reader’s convenience. |

| 76      | Page 16, last paragraph in section R8.1.1.7 | Thompson | Remove the last sentence from the Code Commentary: “Due to the non-homogeneous nature of concrete, calculated crack-width values measured in the field will vary from calculated values and therefore they cannot be directly compared to calculated crack widths.” |

- Section R8.1.1.7 is text copied over from the Code and provided herein for the user’s benefit. Text must remain as-is to properly reflect the Code requirement. Changes to be addressed only if/once the Code has been changed accordingly. |

### 2nd Ballot Results

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Text</th>
<th>Author</th>
<th>Voting Member’s VOTE &amp; COMMENTS</th>
<th>Suggested Change</th>
</tr>
</thead>
</table>
| 74      | 1) Code and TN need to define conditions for transient thermal analysis for the spill condition (leak rate).  


- Garrison was going to forward a copy of EN 1992-1-1:2004 to Ballard for updating the code equations in the TN. |


- Garrison was going to forward a copy of EN 1992-1-1:2004 to Ballard for updating the code equations in the TN. |

| 76      | Page 16, last paragraph in section R8.1.1.7 | Thompson | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic | |

- 2014.02.14 Webinar | |
### ADDITIONAL COMMENTS included with the ballots

<table>
<thead>
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<th>Text</th>
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<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page 4, line 8; Section 1.1</td>
<td>Oliver, Hoff</td>
<td>EDITORIAL: Add “the”&lt;br&gt;“The primary function of TCP is to protect <em><strong>the</strong></em> already highly…”&lt;br&gt;Can we provide some guidance to the owner in this section?</td>
<td>10-21: Hoff comment resolution: The crack width requirements in section 6 are provided to for this purpose. DELETES 1.2.4</td>
</tr>
<tr>
<td>Page 6, Lines 28 - 30</td>
<td>Wu</td>
<td>The liquid tightness criteria are specified in Section 2.1, Items 1 &amp; 2. Why do we need additional tightness criteria on “embedding plates” to be defined by owner?</td>
<td></td>
</tr>
<tr>
<td>Page 7, line 8</td>
<td>Pawski</td>
<td>Referenced section does not match final 376-10&lt;br&gt;1) ACI 376 section 6.3.2 6.3.3”</td>
<td></td>
</tr>
<tr>
<td>Page 7, line 14</td>
<td>Pawski</td>
<td>Referenced section does not match final 376-10&lt;br&gt;2) ACI 376 section 6.3.3 6.3.4”</td>
<td></td>
</tr>
<tr>
<td>Page 9, section 2.3.3, Lines 19</td>
<td>Khalifa</td>
<td>Add ‘separate’ before ‘model’ for clarity.</td>
<td></td>
</tr>
<tr>
<td>Page 8, section 2.3.1, Lines 32, 33</td>
<td>Khalifa</td>
<td>Revise to: Either a proprietary or one of several commercially available FE programs can be used for performing this calculation.</td>
<td></td>
</tr>
<tr>
<td>Page 9, line 24</td>
<td>Hoff</td>
<td>Change this sentence to read: “If Liners are considered as structural members, they should be included if they are considered as structural members too.”</td>
<td>10-21-13&lt;br&gt;Editorial</td>
</tr>
<tr>
<td>Page 10, line 26</td>
<td>Pawski</td>
<td>Use “should” in a non-mandatory TN: “Recognized concrete constitutive models <strong>shall</strong> should be used in the analysis.”</td>
<td>10-21-13&lt;br&gt;Editorial</td>
</tr>
<tr>
<td>Page 10, section 2.4.1, Line 30</td>
<td>Khalifa</td>
<td>Revise to: …account for reduction in tensile stiffness after cracking of concrete including the effects of tension stiffening.</td>
<td>10-21-13&lt;br&gt;Account for reduction in tensile stiffness after cracking of concrete</td>
</tr>
<tr>
<td>Page 11, line 7</td>
<td>Hoff, Widianto</td>
<td>The stress symbols are missing</td>
<td>10-21-13&lt;br&gt;Editorial</td>
</tr>
<tr>
<td>Page 12, lines 10, 11</td>
<td>Hoff</td>
<td>Change to read: “<strong>Since</strong> For the RLG spill case, it is critical that cryogenic liquid be prevented from migrating behind the TCP, and conservative assumptions should be used when selecting material properties.”</td>
<td>10-21-13&lt;br&gt;Editorial</td>
</tr>
<tr>
<td>Page 13, Section 2.5</td>
<td>Wu</td>
<td>The specified code, EN2 part 1-4 &amp; 2.4 does not contain the equations for crack width calculation. The crack width calculation is shown in Section 7.3.4 of EN 1992-1-1 (2004 edition). Also, the equations shown here are not the same as the equations shown in EN 1992-1-1 (2004 edition). Please provide clarification.</td>
<td>10-21-13&lt;br&gt;Modify to address to match code and equations. Same as item 74</td>
</tr>
</tbody>
</table>
To be addressed as future business:

<table>
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<tr>
<th>Author</th>
<th>Comments</th>
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</table>
| Legatos  | Conspicuous by its absence in the TCP-TN write-up is any reference to outer-wall designs that incorporate an impervious, continuous liquid-tight and vapor-tight liner.  
This omission overlooks the crucial role such a liner plays in the formulation of criteria and parameters as they pertain to (a) the serviceability of the outer wall following a spill and/or thermal shock; (b) the specified limits on crack-width, residual wall compression, etc., etc.; and (c) the function, scope and design of the TCP itself.  
Moreover, this omission overlooks the differences between inner-versus-outer, and metallic-versus-non-metallic liners; and the role these differences similarly play in (a) through (c) above.  
If I am not mistaken, the only Code section that fleetingly mentions this subject with respect to the TCP is Section 6.3.3. This article provides guidance on what to do if a “leak-tight membrane/liner” is not used, but does not say anything about what to do in cases where such a liner is in fact used.  
The subject is also covered in 6.3.16.1 1nd 16.3.16.2, but those sections do not relate to the TCP.  
While I have not thoroughly perused the rest of the Code itself to see exactly where else this subject “belongs” and how it should be covered, I believe that TCP-TN coverage might fit in the following sections:  
  Section 1.1 (add a fifth paragraph)  
  Fig. 1.1 (add Fig. 1.1 c)  
  Section 1.2.4  
  Section 2.1 |

2014.02.14 Webinar  
Discuss NAL negative in Reno.  
Note - subsequent to webinar NAL staed he would provide draft wording.
ACI 376 Technical Note on

Thermal Corner Protection Design & Crack Analysis

Reported by ACI Committee 376

Concrete Structures for Refrigerated Liquefied Gas Containment

Neven Krstulovic-Opara* 
Piotr D. Moncarz

Chair 
Secretary

INTRODUCTION

ACI 376 provides requirements and some basic recommendations for the design of the Thermal Corner Protection (TCP). The purpose of this document is to provide further guidance on (a) TCP detailing and (b) TCP liquid-tightness analysis (i.e., crack width calculations). The document therefore consists of two parts:

1. Part 1 – Detailing & Construction Issues: TCP detailing and related design issues are presented in the first part of this document
2. **Part 2 – Crack Width for Liquid Tightness:** One of the key TCP-performance criteria is related to assuring adequate liquid tightness during a spill condition. ACI 376 Code specifies liquid tightness limits in terms of limiting concrete crack widths. The liquid tightness / crack width analysis procedure is presented in the second part of this document, followed by an example outlining proposed analysis steps that would meet ACI 376 Code requirements.
CONTENTS

INTRODUCTION

CHAPTER 1 — TCP DESIGN
1.1—General
1.2—Embedment Plate and Anchor Studs

CHAPTER 2 — LIQUID TIGHTNESS AND CRACK WIDTH ANALYSIS
2.1—General
2.2—Analysis Procedure
2.3—Numerical Model
2.4—Material Constitutive Models
2.5—Crack Width Calculations

APENDICES

APENDIX A — ACI 376 TCP CODE ERQUIREMENTS

REFERENCES
CHAPTER 1 – TCP Design

Figure 1.1: Thermal Corner Protection (TCP) Detail

1.1—General

The thermal corner protection (TCP) is an insulated and liquid tight system located at the bottom of the outer secondary concrete wall, as shown in Figure 1.1 a. The primary function of TCP is to protect already highly stressed wall to slab joint from additional thermal loads during spill conditions. The TCP is designed to provide both (a) a liquid and (b) a thermal barrier at the wall to slab joint, thus protecting the joint from exposure to cryogenic temperatures during a spill condition.

The TCP is connected to a secondary bottom plate that provides a liquid barrier above the slab, as shown in Figure 1.1 a. The TCP is attached to the concrete wall through an embedment plate located at the top of the TCP, as shown in Figure 1.1 b. During the spill condition, the concrete wall above the TCP, the TCP and TCP embedment will be subjected to significant thermal and mechanical loads. The TCP embedment should be designed to remain intact and in place during the spill condition.
The concrete wall above the TCP, directly exposed to spilled product, should remain liquid and substantially vapor tight during the spill condition. This is assured by limiting cracking in the vicinity of the TCP embedment plate during a spill.

The scope of this section is to provide guidelines and best practices for the detailing of the TCP region, i.e., the TCP, the TCP embedment plate and TCP embedment plate anchorage to the outer concrete wall. Information is provided for the evaluation of the embedment plate, design of the anchor studs and attachment to the concrete wall, and for the evaluation of cracking in the embedment zone. Material selection and material requirements used in the design of the 9% nickel-steel TCP and secondary bottom plates may be performed in accordance with API 620.

1.2—Embedment Plate and Anchor Studs

The TCP embedment plate should be designed to resist radial and vertical loads and moments resulting from both (a) thermal gradients, as well as (b) mechanical forces that develop during a spill condition. The TCP design consists of the following steps:

1.2.1 - STEP 1: TCP Load Definition

- Finite element analyses is performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment will be subjected to including thermal, prestress, creep, concrete shrinkage, internal pressure, hydrostatic pressure.
- Various spill levels should be considered to determine the most severe effect on the embedment and concrete wall. This should include spill levels below the top of the TCP which will place the largest temperature differential between the TCP and the concrete wall as well as various spill levels above the TCP up to the full spill level.
- The analysis should be based on both steady state and transient conditions, as specified in ACI 376 Code section 8.4.8. R8.4.8 specifically indicates that during transient conditions an embedment such as the TCP will frequently experience the greatest self-straining forces.

1.2.2 - STEP 2: Embedment Plate Design

- The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall or by other suitable means (e.g., ??). Anchor bolts (studs) should be placed in continuous (circumferential) rows along the concrete wall.
• When the embedment plate is anchored with circumferential studs, a minimum of two rows of studs should be used to anchor the embedment plate. The spacing between mechanical anchors (studs) should be limited to ensure that the axial, bending and shear stresses in the embedment plate are within the allowable stresses.

• Embedment plate and mechanical anchor material as well as the TCP material should be suitable for the product temperature.

• Allowable stresses i.e., material selection and material requirements used in the design of the embedment plates, may be selected in accordance with API 620.

1.2.3 - STEP 3: Anchor Bolt Design

The mechanical anchors bolts (studs) and concrete at the anchor location should meet the requirement for anchoring to the concrete wall defined in the ACI 350 Appendix D.

- The steel strength of the anchor in tension should be as per ACI 350 section D.5.1.
- The concrete breakout strength of the anchor in tension should be checked per ACI 350 section D.5.2.
- The pullout strength of the anchor in tension should be checked per ACI 350 section D.5.3.
- The steel strength of the anchor in shear should be checked per ACI 350 section D.6.1.
- The concrete breakout strength of the anchor in shear should be checked per ACI 350 section D.6.2.
- The concrete pry-out strength of the anchor in shear should be checked per ACI 350 section D.6.3.
- Interaction of tensile and shear forces should be checked per ACI 350 section D.7.
CHAPTER 2 – PART 2: Liquid Tightness and Crack Width Analysis

2.1—General
When subjected to the spill condition, the concrete wall will be loaded with high thermal and mechanical forces. These forces will lead to significant wall cracking. During the spill condition, integrity of the concrete wall must be maintained. As specified in the ACI 376 Code, the wall should remain liquid and vapor tight. More specifically:

1) ACI 376 section 6.3.3: "Unless a leak-tight membrane/liner has been used, a minimum portion of the concrete should remain in compression in accordance with the following:
   a) A compressive zone of either 10% of the section thickness or 3.5 in., whichever is greater should be provided; and
   b) A minimum average compressive stress within the compressive zone of 145 lb/in2 should be maintained."

2) ACI 376 section 6.3.4: "Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness. The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.008 in. within the TCP embedment zone. Recommendations for crack width calculations are provided in 8.1.1.8."

3) ACI 376 section 8.1.1.8 - requires that the cracks widths should be calculated as characteristic and not mean calculated crack widths as per EN 1992-1-1.

Non-linear finite element analysis should be performed to ensure that these requirements are met.

2.2—Analysis Procedure
The analysis procedure consists of the following steps:

2.2.1 - STEP 1: Thermal Analysis
Thermal analysis is performed using Finite Element or Finite Difference approach. Steps include:

1) Modeling
   2) Thermal boundary condition definition/application to equilibrium
   3) Application of LNG spill or external fire temperature loads obtained by considering rate of leakage into annular space and exposed to transient temperatures
4) Continue analysis until steady state final temperatures are reached
5) Repeat for all thermal load cases

2.2.2 - STEP 2: Structural Analysis

Structural Analysis is performed using the Finite Element approach. Steps include

1) Modeling
2) Apply dead load, prestressing and any other steady state load, iterate to equilibrium
3) Check crack widths
4) Apply LNG spill temperature transients and iterate to equilibrium
5) Compute crack widths at times throughout the transient where reinforcing strains are the greatest and exceed the material yield stress
6) Repeat for all thermal load cases

2.3—Numerical Model

Calculation of cracking and crack widths for the LNG spill condition and/or external fire condition shall be performed using a rational engineering analysis. Both linear or non-linear finite element (FE) analysis

2.3.1 Non-Linear FE Analysis

In this case a non-linear finite element program is used in conjunction with

- non-linear FE material constitutive models for concrete and steel, and
- crack width calculations as per Eurocode 2 1992-1-1.

Either a proprietary or a commercially available FE programs can be used. There are several commercially available FE programs that are adequate for performing this calculation. A few of more widely used non-linear FE programs available in the United States include ANSYS\(^1\), ABACUS\(^2\), ADINA\(^3\) and NX NASTRAN\(^4\). There are also many proprietary FE programs that have been designed specifically to consider the cracking problem for reinforced concrete containment structures.

2.3.2 Linear FE Analysis

Linear FE analysis is usually used only in the preliminary design. Two possible approaches include:
a) **Reduced-Stiffness / Cracked-Section Approach:** The calculation is performed using a linear finite element analysis where the reduction in stiffness due to cracking is considered. However, it should be noted that this is a very time consuming process and is thus usually only used in the preliminary design.

b) **Moment-Curvature Approach:** The moment curvature response is obtained using a concrete section analysis program in conjunction with:

- non-linear stress-strain material properties, and
- a non-linear shell formulation that accounts for the cracking induced stiffness redistribution.
- This moment-curvature approach would only be suitable for consideration of the steady state linear thermal gradient case and should also be used only for preliminary design.

### 2.3.3 Mesh Type and Size

The linear or non-linear FE model will usually be axisymmetric or a small slice 3D model of the containment for consideration of the general case of a symmetric LNG spill loads and a larger sector model for consideration of the LNG spill case where non-axisymmetric discontinuities are considered.

Typically, the structural model contains a fine-mesh or a high density of solution points. The model includes the base slab, foundation springs, containment wall, roof structure and local discontinuities, such as the prestressing buttresses. If the liners are considered as structural members, they should be included too.

A more detailed substructure model of the region above the TCP anchorage might be considered in order to reduce the computational demand, provided it can be demonstrated that the boundary conditions and loadings correctly represent the global model.

The reinforcing and prestressing steel may also be modeled and the prestressing forces applied as part of the loading or construction sequence.

### 2.3.4 Loading

The LNG spill case should include hydrostatic pressure from the LNG fluid in the annular space. Dead load, live load and steady state temperatures coincident prior to the LNG spill, shall be applied prior application of the temperature transients.

Nodal temperature transients will typically be computed in a separate heat transfer finite element or finite difference solution. This thermal model is also a high density model which should include concrete foundation,
soil thermal boundary condition, walls, roof and outside or inside ambient temperature boundary conditions. This model should also include the base slab insulation and the thermal corner protection insulation.

### 2.3.5 Heat Analysis

The heat transfer analyses should consider both maximum (95th percentile) and minimum (5th percentile) ambient temperatures. The LNG spill is applied internally to the containment and the adjacent tank fire case is applied externally. The LNG spill load case should also include the vapor temperature generated from the spill above the liquid level. Nodal temperature time histories are computed and mapped to the structural finite element model. The concrete wall internal temperatures from the thermal model are also typically used to determine the placement of normal (A615), cold-temperature (A706) and cryogenic reinforcing complying with the requirements of ACI 376.

The LNG hydrostatic pressure and temperature time histories are applied gradually and the iterative solution computes concrete stresses and strains, crack locations and reinforcing stresses.

### 2.4—Material Constitutive Models

#### 2.4.1 Concrete Constitutive Model

Recognized concrete constitutive models shall be used in the analysis. Examples include material models described by Eurocode 2 and shown in the Figure 2.1 below. The concrete constitutive model should also account for linear tension stiffness effects with tension failure or reduction in stiffness at the cracking strain of the concrete.

*Figure 2.1: Stress-Strain Diagram for Uniaxial Compression from Eurocode 2 1992-1-1*
The $\sigma_c - \varepsilon_c$ material relationship shown in Figure 2.1 is taken from Eurocode 2 Part 1, 4.2.1.3.1 (4.1).

For short term loading the relationship is defined as:

$$\sigma_c/f_c = (k n - n^2)/(1 + n (k-2))$$

where:

- $f_c$ concrete compressive strength at 28 days (N/mm$^2$) $< 0.0$
- $\varepsilon_{cu}$ ultimate strain $< 0.0$
- $n = \varepsilon_c/\varepsilon_{c1}$ (both $< 0.0$)
- $\varepsilon_{c1} = -0.0022$ (strain at the peak stress $f_c$)
- $k = (1.1E_{c,nom}) \varepsilon_{c1}/f_c$
- $E_{c,nom} = E_{cm}/\gamma_c$ (kN/mm$^2$)
- $\gamma_c$ partial safety factor = 1.5 unless justified by adequate control procedures.
- $E_{cm} = 9.5(f_c + 8)^{1/3}$ ($E_{cm}$ in kN/mm$^2$; $f_c$ in N/mm$^2$)

The tension side of the $\sigma_c - \varepsilon_c$ material relationship may be taken as:

$$\sigma_c = E_{cm}\varepsilon_c$$ (N/mm$^2$) for $\sigma_c < f_{cm}$

$$\sigma_c = 0$$ for $\sigma_c > \sigma_c = f_{cm}$

where:

$$f_{cm} = 0.30 f_c^{2/3}$$ (N/mm$^2$)

In reality, the tension softening is usually introduced following rupture of the concrete in order to provide for numerical stability in the solution.

2.4.2 Steel Constitutive Models
Figure 2.2 shows a typical uniaxial stress-strain curve for reinforcing steel and Figure 2.3 a typical uniaxial stress-strain curve for prestressing steel.

**Figure 2.2:** Typical Uniaxial Stress-Strain Curve for Reinforcing Steel from Eurocode 2 1992-1-1

![Typical Uniaxial Stress-Strain Curve for Reinforcing Steel](image1)

**Figure 2.3:** Typical Uniaxial Stress-Strain Curve for Prestressing Steel from Eurocode 2 1992-1-1

![Typical Uniaxial Stress-Strain Curve for Prestressing Steel](image2)

Other concrete and steel constitutive models may be used provided it can be demonstrated that these models accurately characterize material behavior.

### 2.4.3 Selection of Material Parameter Values

Since for the LNG spill case, it is critical that cryogenic liquid be prevented from migrating behind the TCP, conservative assumptions should be used when selecting material properties.

#### 2.4.3.1 - Compressive Response

It should be noted that the extent of the compression zone is not as critical as the size and extent of the cracks. Therefore, the use of the mean compressive concrete strength is adequate for crack width calculations. The mean modulus of elasticity of the reinforcing and prestressing steel and concrete is also considered adequate.

#### 2.4.3.2 - Tensile Properties

For tension properties, the minimum yield strength of the reinforcing should be considered to maximize the crack width. Also, if tensile strength of the concrete is considered, the analysis should evaluate the 95th and 5th percentile concrete tensile strength limits. A more conservative approach would be to consider no tensile capacity of the concrete in the analysis.
2.4.3.3 - Temperature Effects on Material Properties

Improved material properties at low temperature, should not be used unless adequate cryogenic testing has been carried out to confirm these material properties. The variation of the mean coefficient of thermal expansion with temperature should also be considered in the solution.

2.5—Crack Width Calculations

The Code suggests that Eurocode 2 Part 1 4.4.2.4, (4.80) be the basis for calculation of crack widths. In this approach crack width is determined from steel strains using the following relationship:

\[ w_k = \beta s_m \varepsilon_{sm} \]  \hspace{1cm} (14)

where \( w_k \) is the 95\(^{th} \) percentile crack width, \( \varepsilon_{sm} \) is the mean steel strain, \( s_m \) is the average final crack spacing and \( \beta \) is a design value that can be taken as:

- 1.7 for load induced cracking and for restraint cracking in section with minimum dimension in excess of 800 mm, or
- 1.3 for restraint cracking in sections with a minimum dimension depth, breadth or thickness, (whichever is the lesser) of 300 mm or less.

The average final crack spacing, \( s_m \), is computed from Eurocode 2 Part 1, 4.4.2.4 (4.82) as:

\[ s_m = 50 + 0.25k_1 kk_2 \phi / \rho_r \]  \hspace{1cm} (15)

where:

- \( \phi \) is the barsize or average bar size in mm  \hspace{1cm} (16)
- \( k_1 = 0.8 \) for high bond bars and 1.6 for plain bars  \hspace{1cm} (17)
- \( k = 0.8 \) for tensile stresses that are due to intrinsic deformations  \hspace{1cm} (18)
- \( k_2 \) is a coefficient which accounts for the form of the strain distribution and is between 0.5 for bending and 1.0 for pure tension.  \hspace{1cm} (19)
- \( \rho_r \) is the effective reinforcing ratio, \( A_r/A_{c,eff} \), where \( A_r \) is the area of reinforcement contained within the effective tension area, \( A_{c,eff} \)  \hspace{1cm} (20)

The mean strain value, \( \varepsilon_{sm} \), should be computed directly using the non-linear finite element model and considering all loads existing at the time of cracking. More specifically, the mean strain is obtained by averaging calculated strain over the length of steel that has exceeded the yield limit. In other words, for a single piece of reinforcing steel that has exceeded yield, \( \varepsilon_{sm} \) would be computed as the integrated strain over the length of the plastic zone of the reinforcing divided by the length of the plastic zone.
REFERENCES

1. ANSYS Inc., Canonsburg, PA
2. ABACUS, Inc., Providence, RI
3. ADINA R & D, Inc., Watertown, MA
4. Siemens PLM Software, Plano TX
5. EUROCODE 2 Design of concrete structures – Part 1 General rules and rules for buildings
### Appendix A: ACI 376 Code TCP Requirements

#### CHAPTER 2—NOTATION AND TERMINOLOGY

**thermal corner protection (TCP)**—insulated and liquid tight system to protect the outer tank from thermal shock.

**calculated crack width**—crack width calculated using a concrete constitutive model defined in 8.1.1.7.

#### CHAPTER 6—MINIMUM PERFORMANCE REQUIREMENTS

6.3.2—Under spill conditions, the concrete above the thermal corner protection (TCP) should remain liquid tight, based upon minimum depths of compression and precompression.

6.3.4—Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness. The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.004 in. within the TCP embedment zone.

#### CHAPTER 8—ANALYSIS & DESIGN

| 8.1.1.7—Cracking and tension stiffening should be included by appropriate modification of the material stress strain relationship or by the use of finite elements | R8.1.1.7—The Eurocode 2 is recommended for determining calculated crack widths. In this case, the calculated crack widths are characteristic and not mean calculated crack widths |

that have the capability of cracking under tension, and crushing under compression as well as the ability to include reinforcing steel.

Unless otherwise specified, the concrete constitutive mode from European Code should be used for determining calculated crack widths.

Extensive field experience with liquid retaining and offshore concrete structures has demonstrated that satisfactory liquid tightness and liquid retaining performance can be achieved by imposing calculated crack width limits.

However, it must be noted that calculated crack width represents an average numerical value that is not directly equivalent to calculated crack width measured in the field. Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.
Fig. A6(c)—Example of fixed-base full containment for LiG - Detail at foundation.
ACI 376 Technical Note on

Design and Analysis of the TCP Embedment Zone

Reported by ACI Committee 376

Concrete Structures for Refrigerated Liquefied Gas Containment

INTRODUCTION

ACI 376 provides requirements and some basic recommendations for the design of the Thermal Corner Protection (TCP) embedment zone. The purpose of this Technical Note is to provide further guidance for (a) design and analysis of the TCP anchorage and (b) liquid-tightness analysis in the TCP embedment zone (i.e., crack width calculations). The document therefore consists of two parts:

1. Part 1 – Detailing & Construction Issues: TCP detailing and related design issues are presented in the first part of this document
2. **Part 2 – Crack Width for Liquid Tightness**: One of the key TCP-performance criteria is related to assuring adequate liquid tightness during a spill condition. ACI 376 Code specifies liquid tightness limits in terms of limiting concrete crack widths. The liquid tightness / crack width analysis procedure is presented in the second part of this document, followed by an example outlining proposed analysis steps that would meet ACI 376 Code requirements.

Although the code and this TN do not explicitly define leak tightness criteria for the anchorage and embedment, the design and construction of these components should be carried out with the clear objective of protecting the corner joint from product temperatures.
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APENDIX A – ACI 376 TCP CODE REQUIREMENTS

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CHAPTER 1 – TCP Design

1.1—General

The thermal corner protection (TCP) is an insulated and liquid tight system located at the bottom of the outer secondary concrete wall, as shown in Figure 1.1 a. The primary function of TCP is to protect the already highly stressed wall to slab joint from additional thermal loads during spill conditions. The TCP is designed to provide both (a) a liquid and (b) a thermal barrier at the wall to slab joint, thus protecting the joint from exposure to cryogenic temperatures during a spill condition.

The TCP is connected to a secondary bottom plate that provides a liquid barrier above the slab, as shown in Figure 1.1 a. The TCP is attached to the concrete wall through an embedment plate located at the top of the TCP, as shown in Figure 1.1 b. During the spill condition, the concrete wall above the TCP, the TCP and TCP embedment will be subjected to significant thermal and mechanical loads. The TCP embedment should be designed to remain functional and in place during the spill condition.

Figure 1.1: Thermal Corner Protection (TCP) Detail
The concrete wall above the TCP, directly exposed to spilled product, should remain liquid tight and substantially vapor tight during the spill condition. This is assured by maintaining a compression zone in the wall exposed to the spill and by limiting crack width on the inside face of the wall in the TCP embedment zone plate during a spill.

The scope of this section is to provide guidelines and best practices for the detailing of the TCP region, i.e., the TCP, the TCP embedment plate and TCP embedment plate anchorage to the outer concrete wall. Information is provided for the evaluation of the embedment plate, design of anchors and attachment to the concrete wall, and for the evaluation of cracking in the embedment zone.

1.2—Embedment Plate and Anchors

The TCP embedment plate should be designed to resist radial and vertical loads and moments resulting from both (a) thermal gradients, as well as (b) mechanical forces that develop during a spill condition including SSE$_{AFT}$.

The TCP design consists of the following steps:

1.2.1 - STEP 1: TCP Load Definition

- Finite element analyses are performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment will be subjected to including thermal, prestress, creep, concrete shrinkage, internal pressure, hydrostatic pressure and hydrodynamic pressure due to seismic aftershock (SSE$_{AFT}$). Initial temperatures and conditions should be selected so as to maximize the demand under consideration. For instance for the design of the anchors the critical condition is likely to be warm wall (summer) a cold thermal shock to the embedment, thereby creating maximum strain across the section.

- Various spill levels should be considered to determine the most severe effect on the embedment and concrete wall. This should include a spill level located just below the top of the TCP which will place the largest temperature differential between the TCP and the concrete. A minimum of three levels should be considered for spill levels above the TCP, 1) at top of the TCP embedment zone, 2) at mid-height, and 3) at full spill level.

- The analysis should be based on both steady state and transient conditions, as specified in ACI 376 Code section 8.4.8. R8.4.8 specifically indicates that during transient conditions an embedment such as the TCP will frequently experience the greatest self-straining forces.

1.2.2 - STEP 2: Embedment Plate Design

- The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall.
• The embedment plate should be anchored with a minimum of two rows of circumferential anchors. The spacing between anchors has significant impact on the TCP embedment performance and thus should be considered in design.

• Embedment plate and mechanical anchor material as well as the TCP material should be suitable for the product temperature.

• Allowable stresses i.e., material selection and material requirements used in the design of the embedment plates, may be selected in accordance with API 620.

• Anchor spacings should be selected so as to be multiples of the bar spacing to enable a clash-free design.

1.2.3 - STEP 3: Anchorage Design

The mechanical anchorage (anchors bolts or studs) and concrete at the anchor location should meet the requirement for anchoring to the concrete wall defined in the ACI 350 Appendix D.

1.2.4 - STEP 4: Liquid Tightness

Liquid tightness at the embedment plate should be considered in the details and design of the anchorage as defined by the owner.

Note - consensus at 2013.10.21 Phoenix meeting was new "1.2.4 Step 4" is not needed and should be deleted in its entirety. Shown for information and is to be deleted.
CHAPTER 2 – PART 2: Liquid Tightness and Crack Width Analysis

2.1—General

During the spill condition, the secondary concrete wall will be subjected to high-large forces due to mechanical loads and thermal effects that will lead to significant wall cracking. Integrity of the concrete wall must be maintained. As specified in the ACI 376 Code, the wall should remain liquid and substantially vapor tight. More specifically:

1) ACI 376 section 6.3.2: “Unless a leak-tight membrane/liner has been used, a minimum portion of the concrete should remain in compression in accordance with the following:
   a) A compressive zone of either 10% of the section thickness or 3.5 in., whichever is greater shall be provided; and
   b) A minimum average compressive stress within the compressive zone of 145 lb/in² should be maintained.”

2) ACI 376 section 6.3.3: “Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness. The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.008 in. within the TCP embedment zone. Recommendations for crack width calculations are provided in 8.1.1.8.”

3) ACI 376 section 8.1.1.8 - requires that the cracks widths should be calculated as characteristic and not mean crack widths.

Non-linear finite element analysis should be performed to ensure that these requirements are met.

2.2—Analysis Procedure

The analysis procedure consists of the following steps:

2.2.1 - STEP 1: Thermal Analysis

Thermal analysis is performed based on a thermal model using Finite Element or Finite Difference approach. Steps include:

1) Modeling including specific tank geometry and material thermal properties

2) Thermal boundary condition definition/application to equilibrium

3) Application of RLG spill temperature loads obtained by considering rate of leakage into annular space and exposed to transient temperatures
4) Continue analysis until steady state temperature distribution is obtained
5) Repeat for all thermal load cases

2.2.2 - STEP 2: Structural Analysis

Structural Analysis is performed based on the stress model using the Finite Element approach. Steps include:

1) Modeling
2) To establish initial conditions, apply dead load, prestressing, normal operating thermal and any other steady state load, then iterate to equilibrium
3) Apply RLG spill temperature transients and iterate to equilibrium
4) Beginning with the initial condition defined in step 2, compute crack widths at time-steps throughout the transient where reinforcing strains are the greatest. Furthermore, at each time step determine the adequacy of the compression zone.
5) Repeat for all thermal load cases

2.3—Numerical Model

Calculation of cracking and crack widths for the RLG spill condition shall be performed using a rational engineering analysis. Linear or non-linear finite element (FE) analysis should be used as discussed in 2.3.1 and 2.3.2.

2.3.1 Non-Linear FE Analysis

In this case a non-linear finite element program is used by:

- Implementing the non-linear material constitutive relationship for concrete and steel,
- Carrying out FE analysis to obtain stress/strain contours, and
- Performing FE analysis post process to calculate characteristic crack width, following a method such as Eurocode EN 2 1992-1-1 (see section 2.5 in this TN).

Either a proprietary or one of several commercially available FE programs can be used for performing this calculation. A few of more widely used non-linear FE programs available in the United States include ANSYS\textsuperscript{1}, ABACUS\textsuperscript{2}, ADINA\textsuperscript{3} and NX NASTRAN\textsuperscript{4}. There are also many proprietary FE programs that have been designed specifically to consider the cracking problem for reinforced concrete containment structures.

2.3.2 Simplified FE Analysis
Simplified FE analysis is usually used only in the preliminary design. Two possible approaches include:

   a) **Reduced-Stiffness / Cracked-Section Approach**: The calculation is performed using a linear finite element analysis where the reduction in stiffness due to cracking is considered.

   b) **Moment-Curvature Approach**: The moment curvature properties are obtained using a concrete section analysis by implementing in conjunction with:

   - non-linear stress-strain material properties, and
   - a non-linear shell formulation that accounts for the cracking induced stiffness redistribution.

### 2.3.3 Mesh Type and Size

The linear or non-linear FE model will usually be axisymmetric or a 3D model of the containment for consideration of the general case of a symmetric RLG spill loads and a separate model for consideration of the RLG spill case where non-axisymmetric discontinuities are considered.

Typically, the structural model contains a fine-mesh or a high density of solution points. The model includes the base slab, foundation springs, containment wall, roof structure and local discontinuities, such as the prestressing buttresses. Liners should be included if they are considered as structural members.

A more detailed substructure model of the region above the TCP anchorage might be considered in order to reduce the computational demand, provided it can be demonstrated that the boundary conditions and loadings correctly represent the global model.

The reinforcing and prestressing steel should also be modeled and the prestressing forces applied as part of the loading or construction sequence.

### 2.3.4 Loading

The RLG spill case should include hydrostatic pressure from the RLG fluid in the annular space. Dead load, live load and steady state temperatures coincident prior to the RLG spill, shall be applied prior application of the temperature transients.

Nodal temperature transients will typically be computed in a separate heat transfer finite element or finite difference solution. **The thermal model used for determining nodal temperatures** This thermal model is also a high density model which should include concrete foundation, soil thermal boundary condition, walls, roof and...
outside or inside ambient temperature boundary conditions. This model should also include the base slab insulation and the thermal corner protection insulation.

2.3.5 Thermal Analysis

The heat transfer analyses should consider both maximum (95\textsuperscript{th} percentile) and minimum (5\textsuperscript{th} percentile) ambient temperatures. The RLG spill is applied internally to the containment \( V \). The RLG spill load case should also include the vapor temperature generated from the spill above the liquid level. Nodal temperature time histories are computed and mapped to the structural finite element model. The concrete wall internal temperatures from the thermal model are also typically used for selection and placement of reinforcement complying with the requirements of ACI 376.

The RLG hydrostatic pressure and temperature time histories are applied gradually and the iterative solution computes concrete stresses and strains, crack locations and reinforcing stresses.

2.4—Material Constitutive Models

2.4.1 Concrete Constitutive Model

Recognized concrete constitutive models should be used in the analysis. Examples include material models described by Eurocode 2\textsuperscript{5} and shown in the Figure 2.1 below. The concrete constitutive model should also account for reduction in tensile stiffness after cracking of concrete including the effects of tension stiffening.

\textbf{Figure 2.1:} Stress-Strain Diagram for Uniaxial Compression from Eurocode EN 2 1992-1-1

\[ \sigma_c - \varepsilon_c \] material relationship shown in Figure 2.1 is taken from Eurocode EN 2 Part 1, 4.2.1.3.1 (4.1).
For short term loading the relationship is defined as:

$$\sigma_c/f_c = (k'n^2)/(1 + n(k-2)) \tag{1}$$

where:

- $f_c$ concrete compressive strength at 28 days (N/mm$^2$) < 0.0 \tag{2}
- $\varepsilon_{cu}$ ultimate strain < 0.0 \tag{3}
- $n = \varepsilon_c/\varepsilon_{c1}$ (both < 0.0) \tag{4}
- $\varepsilon_{c1} = -0.0022$ (strain at the peak stress $f_c$) \tag{5}
- $k = (1.1E_{c,nom})\varepsilon_{c1}/f_c$ \tag{6}
- $E_{c,nom} = E_{cm}/\gamma_c$ (kN/mm$^2$) \tag{7}
- $\gamma_c$ partial safety factor = 1.5 unless justified by adequate control procedures. \tag{8}
- $E_{cm} = 9.5(f_c + 8)^{1/3}$ (E$cm$ in kN/mm$^2$; $f_c$ in N/mm$^2$) \tag{9}

The tension side of the $f_c - \varepsilon_c$ material relationship may be taken as:

$$\sigma_c = E_{cm}\varepsilon_c \text{ (N/mm}^2) \text{ for } \sigma_c < f_{ctm} \tag{10}$$

$$\sigma_c = 0 \text{ for } \sigma_c > f_{ctm} \tag{11}$$

where:

$$f_{ctm} = 0.30f_c^{2/3} \text{ (N/mm}^2) \tag{13}$$

Tension softening is usually introduced following rupture of the concrete in order to provide for numerical stability in the solution.

2.4.2 Steel Constitutive Models

Figure 2.2 shows a typical uniaxial stress strain curve for reinforcing steel and Figure 2.3 a typical uniaxial stress-strain curve for prestressing steel.
Other concrete and steel constitutive models may be used provided it can be demonstrated that these models accurately characterize material behavior.

2.4.3 Selection of Material Parameter Values

For the RLG spill case, it is critical that cryogenic liquid be prevented from migrating behind the TCP, and conservative assumptions should be used when selecting material properties.

2.4.3.1 - Compressive Response

It should be noted that the extent of the compression zone is not as critical as the size and extent of the cracks. Therefore, the use of the mean compressive concrete strength is adequate for crack width calculations. The mean modulus of elasticity of the reinforcing and prestressing steel and concrete is also considered adequate.

2.4.3.2 - Tensile Properties

For tension properties, the minimum yield strength of the reinforcing should be considered to maximize the crack width. Also, if tensile strength of the concrete is considered, the analysis should evaluate the 95th and 5th percentile concrete tensile strength limits. A more conservative approach would be to consider no tensile capacity of the concrete in the analysis.

2.4.3.3 - Temperature Effects on Material Properties

Improved material properties at low temperature, should not be used unless adequate cryogenic testing has been carried out to confirm these material properties. The variation of the mean coefficient of thermal expansion with temperature should also be considered in the solution.
2.5—Crack Width Calculations

The Code suggests that Eurocode EN 2 Part 1 4.4.2.4, (4.80) be the basis for calculation of crack widths. In this approach crack width is determined from steel strains using the following relationship:

\[ w_k = \beta s_{rm} \varepsilon_{sm} \]  

where \( w_k \) is the 95th percentile crack width, \( \varepsilon_{sm} \) is the mean steel strain, \( s_{rm} \) is the average final crack spacing and \( \beta \) is a design value that can be taken as:

- 1.7 for load induced cracking and for restraint cracking in section with minimum dimension in excess of 800 mm, or
- 1.3 for restraint cracking in sections with a minimum dimension depth, breadth or thickness, (whichever is the lesser) of 300 mm or less.

The average final crack spacing, \( s_{rm} \), is computed from Eurocode 2 Part 1, 4.4.2.4 (4.82) as:

\[ s_{rm} = 50 + 0.25k \_OPTIONAL_k1 k2 \phi / \rho_r \]  

where:

- \( \phi \) is the barsize or average bar size in mm
- \( k_1 = 0.8 \) for high bond bars and 1.6 for plain bars
- \( k = 0.8 \) for tensile stresses that are due to intrinsic deformations
- \( k_2 \) is a coefficient which accounts for the form of the strain distribution and is between 0.5 for bending and 1.0 for pure tension.
- \( \rho_r \) is the effective reinforcing ratio, \( A_s / A_{c,eff} \), where \( A_s \) is the area of reinforcement contained within the effective tension area, \( A_{c,eff} \).

The mean strain value, \( \varepsilon_{sm} \), should be computed directly using the non-linear finite element model and considering all loads existing at the time of cracking. More specifically, the mean strain is obtained by averaging calculated strain over the length of steel that has exceeded the yield limit. In other words, for a single piece of reinforcing steel that has exceeded yield, \( \varepsilon_{sm} \) would be computed as the integrated strain over the length of the plastic zone of the reinforcing divided by the length of the plastic zone.

REFERENCES

1. ANSYS Inc., Canonsburg, PA
2. ABACUS, Inc., Providence, RI
3. ADINA R & D, Inc., Watertown, MA
4. Siemens PLM Software, Plano TX
5. EUROCODE 2 Design of concrete structures – Part 1 General rules and rules for buildings
Appendix A: ACI 376 Code TCP Requirements

CHAPTER 2—NOTATION AND TERMINOLOGY

thermal corner protection (TCP)—insulated and liquid tight system to protect the outer tank from thermal shock.

calculated crack width—crack width calculated using a concrete constitutive model defined in 8.1.1.7.

CHAPTER 6—MINIMUM PERFORMANCE REQUIREMENTS

6.3.2—Under spill conditions, the concrete above the thermal corner protection (TCP) should remain liquid tight, based upon minimum depths of compression and precompression.

6.3.4—Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness.

The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.008 in. within the TCP embedment zone.

CHAPTER 8—ANALYSIS & DESIGN

8.1.1.7—Cracking and tension stiffening should be included by appropriate modification of the material stress strain relationship or by the use of finite elements that have the capability of cracking under

R8.1.1.7—The Eurocode 2 is recommended for determining calculated crack widths. In this case, the calculated crack widths are characteristic and not mean calculated crack widths.
tension, and crushing under compression as well as the ability to include reinforcing steel.

Unless otherwise specified, the concrete constitutive mode from European Code should be used for determining calculated crack widths.

Extensive field experience with liquid retaining and offshore concrete structures has demonstrated that satisfactory liquid tightness and liquid retaining performance can be achieved by imposing calculated crack width limits.

However, it must be noted that calculated crack width represents an average numerical value that is not directly equivalent to calculated crack width measured in the field. Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.
Fig. A 6(c)—Example of fixed-base full containment for LNG - Detail at foundation.
ACI 376 Technical Note on

Design and Analysis of the TCP Embedment Zone

Reported by ACI Committee 376

Concrete Structures for Refrigerated Liquefied Gas Containment

Neven Krstulovic-Opara*  Piotr D. Moncarz
Chair  Secretary

Junius Allen  Alan D. Hatfield  Thomas R. Howe  Robert W. Nussmeier
Thomas A. Ballard*  Huanyun Hashmi  Dajiu Jiang  Rolf P. Pawski*
Dale Berner  Kare Hjorteset  Jameel U. Khalifa  Ramanujam S. Rajan
Mike S. Brannan  George C. Hoff*  Nicholas A. Legatos  William E. Rushing
Hamish Douglas*  Richard Hoffmann  Praveen K. Malhotra  Robert W. Sward
Jeffrey Garrison*  John Holleyoak  Keith A. Mash*  Eric S. Thompson
Charles S. Hanskat  Joseph M. Hoptay*  Stephen W. Meier  Sheng-Chi Wu

* Contributing Member

INTRODUCTION

ACI 376 provides requirements and some basic recommendations for the design of the Thermal Corner Protection (TCP) embedment zone. The purpose of this Technical Note is to provide further guidance for (a) design and analysis of the TCP anchorage and (b) liquid-tightness analysis in the TCP embedment zone (i.e., crack width calculations). The document therefore consists of two parts:

1. Part 1 – Detailing & Construction Issues: TCP detailing and related design issues are presented in the first part of this document
2. **Part 2 – Crack Width for Liquid Tightness**: One of the key TCP-performance criteria is related to assuring adequate liquid tightness during a spill condition. ACI 376 Code specifies liquid tightness limits in terms of limiting concrete crack widths. The liquid tightness / crack width analysis procedure is presented in the second part of this document, followed by an example outlining proposed analysis steps that would meet ACI 376 Code requirements.

Although the code and this TN do not explicitly define leak tightness criteria for the anchorage and embedment, the design and construction of these components should be carried out with the clear objective of protecting the corner joint from product temperatures.

*Comment [LE6]*: Part of Ref. 001: T.Ballard negative. Draft of new paragraph for committee consideration agreed to at Minneapolis – 2013.04.13.
CONTENTS

INTRODUCTION

CHAPTER 1 – TCP DESIGN
1.1—General
1.2—Embedment Plate and Anchorage

CHAPTER 2 – LIQUID TIGHTNESS AND CRACK WIDTH ANALYSIS
2.1—General
2.2—Analysis Procedure
2.3—Numerical Model
2.4—Material Constitutive Models
2.5—Crack Width Calculations

APENDICES

APENDIX A – ACI 376 TCP CODE ERQUIREMENTS

REFERENCES
CHAPTER 1 – TCP Design

1.1—General

The thermal corner protection (TCP) is an insulated and liquid tight system located at the bottom of the outer secondary concrete wall, as shown in Figure 1.1 a. The primary function of TCP is to protect already highly stressed wall to slab joint from additional thermal loads during spill conditions. The TCP is designed to provide both (a) a liquid and (b) a thermal barrier at the wall to slab joint, thus protecting the joint from exposure to cryogenic temperatures during a spill condition.

The TCP is connected to a secondary bottom plate that provides a liquid barrier above the slab, as shown in Figure 1.1 a. The TCP is attached to the concrete wall through an embedment plate located at the top of the TCP, as shown in Figure 1.1 b. During the spill condition, the concrete wall above the TCP, the TCP and TCP embedment will be subjected to significant thermal and mechanical loads. The TCP embedment should be designed to remain functional and in place during the spill condition.

Figure 1.1: Thermal Corner Protection (TCP) Detail
The concrete wall above the TCP, directly exposed to spilled product, should remain liquid tight and substantially vapor tight during the spill condition. This is assured by maintaining a compression zone in the wall exposed to the spill and by limiting crack width on the inside face of the wall in the TCP embedment zone plate during a spill.

The scope of this section is to provide guidelines and best practices for the detailing of the TCP region, i.e., the TCP, the TCP embedment plate and TCP embedment plate anchorage to the outer concrete wall. Information is provided for the evaluation of the embedment plate, design of anchors and attachment to the concrete wall, and for the evaluation of cracking in the embedment zone.

1.2—Embedment Plate and Anchors

The TCP embedment plate should be designed to resist radial and vertical loads and moments resulting from both (a) thermal gradients, as well as (b) mechanical forces that develop during a spill condition including SSE and hydrostatic pressure due to seismic aftershock $(SSE_{AFT})$. Initial temperatures and conditions should be selected so as to maximize the demand under consideration. For instance for the design of the anchors the critical condition is likely to be warm wall (summer) a cold thermal shock to the embedment thereby creating maximum strain across the section.

Various spill levels should be considered to determine the most severe effect on the embedment and concrete wall. This should include a spill level located just below the top of the TCP which will place the largest temperature differential between the TCP and the concrete. A minimum of three levels should be considered for spill levels above the TCP, 1) at top of the TCP embedment zone, 2) at mid-height, and 3) at full spill level.

The analysis should be based on both steady state and transient conditions, as specified in ACI 376 Code section 8.4.8. R8.4.8 specifically indicates that during transient conditions an embedment such as the TCP will frequently experience the greatest self-straining forces.

1.2.2—STEP 2: Embedment Plate Design

The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall.
• The embedment plate should be anchored with a minimum of two rows of circumferential anchors. The spacing between anchors has significant impact on the TCP embedment performance and thus should be considered in design.

• Embedment plate and mechanical anchor material as well as the TCP material should be suitable for the product temperature.

• Allowable stresses i.e., material selection and material requirements used in the design of the embedment plates, may be selected in accordance with API 620.

• Anchor spacings should be selected so as to be multiples of the bar spacing to enable a clash-free design.

1.2.3 - STEP 3: Anchorage Design

The mechanical anchorage (anchors bolts or studs) and concrete at the anchor location should meet the requirement for anchoring to the concrete wall defined in the ACI 350 Appendix D.

1.2.4 - STEP 4: Liquid Tightness

Liquid tightness at the embedment plate should be considered in the details and design of the anchorage as defined by the owner.

Note - consensus at 2013.10.21 Phoenix meeting was new "1.2.4 Step 4" is not needed and should be deleted in its entirety. Shown for information and is to be deleted.
CHAPTER 2 – PART 2: Liquid Tightness and Crack Width Analysis

2.1—General

During the spill condition, the secondary concrete wall will be subjected to high-large forces due to mechanical loads and thermal effects that will lead to significant wall cracking. Integrity of the concrete wall must be maintained. As specified in the ACI 376 Code, the wall should remain liquid and substantially vapor tight. More specifically:

1) ACI 376 section 6.3.2: "Unless a leak-tight membrane/liner has been used, a minimum portion of the concrete should remain in compression in accordance with the following:
   a) A compressive zone of either 10% of the section thickness or 3.5 in., whichever is greater, shall be provided; and
   b) A minimum average compressive stress within the compressive zone of 145 lb/in² should be maintained."

2) ACI 376 section 6.3.3: "Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness. The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.008 in. within the TCP embedment zone. Recommendations for crack width calculations are provided in 8.1.1.8."

3) ACI 376 section 8.1.1.8 - requires that the cracks widths should be calculated as characteristic and not mean crack widths.

Non-linear finite element analysis should be performed to ensure that these requirements are met.

2.2—Analysis Procedure

The analysis procedure consists of the following steps:

2.2.1 - STEP 1: Thermal Analysis

Thermal analysis is performed based on a thermal model using Finite Element or Finite Difference approach. Steps include:

1) Modeling including specific tank geometry and material thermal properties
2) Thermal boundary condition definition/application to equilibrium
3) Application of RLG spill temperature loads obtained by considering rate of leakage into annular space and exposed to transient temperatures.
4) Continue analysis until steady state temperature distribution is obtained

5) Repeat for all thermal load cases

2.2.2 - STEP 2: Structural Analysis

Structural Analysis is performed based on the stress model using the Finite Element approach. Steps include

1) Modeling

2) To establish initial conditions, apply dead load, prestressing, normal operating thermal and any other steady state load, then iterate to equilibrium

3) Apply RLG spill temperature transients and iterate to equilibrium

4) Beginning with the initial condition defined in step 2, compute crack widths at time-steps throughout the transient where reinforcing strains are the greatest. Furthermore, at each time step determine the adequacy of the compression zone.

5) Repeat for all thermal load cases

2.3—Numerical Model

Calculation of cracking and crack widths for the RLG spill condition shall be performed using a rational engineering analysis. Linear or non-linear finite element (FE) analysis should be used as discussed in 2.3.1 and 2.3.2.

2.3.1 Non-Linear FE Analysis

In this case a non-linear finite element program is used by:

- Implementing the non-linear material constitutive relationship for concrete and steel,
- Carrying out FE analysis to obtain stress/strain contours, and
- Performing FE analysis post process to calculate characteristic crack width, following a method such as Eurocode EN 2 1992-1-1 (see section 2.5 in this TN).

Either a proprietary or one of several commercially available FE programs can be used for performing this calculation. A few of more widely used non-linear FE programs available in the United States include ANSYS, ABACUS, ADINA and NX NASTRAN. There are also many proprietary FE programs that have been designed specifically to consider the cracking problem for reinforced concrete containment structures.

2.3.2 Simplified FE Analysis
Simplified FE analysis is usually used only in the preliminary design. Two possible approaches include:

a) Reduced-Stiffness / Cracked-Section Approach: The calculation is performed using a linear finite element analysis where the reduction in stiffness due to cracking is considered.

b) Moment-Curvature Approach: The moment curvature properties are obtained using a concrete section analysis by implementing in conjunction with:
- non-linear stress-strain material properties, and
- a non-linear shell formulation that accounts for the cracking induced stiffness redistribution.

2.3.3 Mesh Type and Size
The linear or non-linear FE model will usually be axisymmetric or a 3D model of the containment for consideration of the general case of a symmetric RLG spill loads and a separate model for consideration of the RLG spill case where non-axisymmetric discontinuities are considered.

Typically, the structural model contains a fine-mesh or a high density of solution points. The model includes the base slab, foundation springs, containment wall, roof structure and local discontinuities, such as the prestressing buttresses. Liners should be included if they are considered as structural members.

A more detailed substructure model of the region above the TCP anchorage might be considered in order to reduce the computational demand, provided it can be demonstrated that the boundary conditions and loadings correctly represent the global model.

The reinforcing and prestressing steel should also be modeled and the prestressing forces applied as part of the loading or construction sequence.

2.3.4 Loading
The RLG spill case should include hydrostatic pressure from the RLG fluid in the annular space. Dead load, live load and steady state temperatures coincident prior to the RLG spill, shall be applied prior application of the temperature transients.

Nodal temperature transients will typically be computed in a separate heat transfer finite element or finite difference solution. The thermal model used for determining nodal temperatures should be a high density model which should include concrete foundation, soil thermal boundary condition, walls, roof and...
outside or inside ambient temperature boundary conditions. This model should also include the base slab insulation and the thermal corner protection insulation.

2.3.5 [Thermal] Analysis

The heat transfer analyses should consider both maximum (95th percentile) and minimum (5th percentile) ambient temperatures. The RLG spill is applied internally to the containment. The RLG spill load case should also include the vapor temperature generated from the spill above the liquid level. Nodal temperature time histories are computed and mapped to the structural finite element model. The concrete wall internal temperatures from the thermal model are also typically used for selection and placement of reinforcement complying with the requirements of ACI 376.

The RLG hydrostatic pressure and temperature time histories are applied gradually and the iterative solution computes concrete stresses and strains, crack locations and reinforcing stresses.

2.4—Material Constitutive Models

2.4.1 Concrete Constitutive Model

Recognized concrete constitutive models should be used in the analysis. Examples include material models described by Eurocode 2 and shown in the Figure 2.1 below. The concrete constitutive model should also account for reduction in tensile stiffness after cracking of concrete including the effects of tension stiffening.

Figure 2.1: Stress-Strain Diagram for Uniaxial Compression from Eurocode EN 2 1992-1-1

The $\sigma_c - \varepsilon_c$ material relationship shown in Figure 2.1 is taken from Eurocode EN Part 1.4.2.1.3.1 (4.1).
For short term loading the relationship is defined as:

\[ \sigma / f_c = (k n - n^2)[1 + n(k-2)] \]  

(1)

where:

- \( f_c \) = concrete compressive strength at 28 days (N/mm\(^2\)) < 0.0  
- \( \varepsilon_{cu} \) = ultimate strain < 0.0  
- \( \varepsilon_{c1} \) = -0.0022 (strain at the peak stress \( f_c \))  
- \( k \) = \((1.1E_{cm})\varepsilon_{c1}/f_c\)  
- \( E_{cm} = 9.5(f_c + 8)^{1/3} \) (E\(_{cm}\) in kN/mm\(^2\); \( f_c\) in N/mm\(^2\))  
- \( \gamma_c \) = partial safety factor = 1.5 unless justified by adequate control procedures.  

The tension side of the \( f_c - \varepsilon_c \) material relationship may be taken as:

\[ \sigma_c = \varepsilon_{cm} \varepsilon_c \text{ (N/mm}\(^2\)) \text{ for } \sigma_c < f_{ctm} \]  

(10)

\[ \sigma_c = 0 \text{ for } \sigma_c \geq f_{ctm} \]  

(11)

where:

\[ f_{ctm} = 0.30f_c^{2/3} \text{ (N/mm}\(^2\)) \]  

(13)

Tension softening is usually introduced following rupture of the concrete in order to provide for numerical stability in the solution.

2.4.2 Steel Constitutive Models

Figure 2.2 shows a typical uniaxial stress strain curve for reinforcing steel and Figure 2.3 a typical uniaxial stress-strain curve for prestressing steel.

Figure 2.2: Typical Uniaxial Stress-Strain Curve for Reinforcing Steel from Eurocode EN 2 1992-1-1

Figure 2.3: Typical Uniaxial Stress-Strain Curve for Prestressing Steel from Eurocode EN 2 1992-1-1
Other concrete and steel constitutive models may be used provided it can be demonstrated that these models accurately characterize material behavior.

2.4.3 Selection of Material Parameter Values

For the LNG spill case, it is critical that cryogenic liquid be prevented from migrating behind the TCP, and conservative assumptions should be used when selecting material properties.

2.4.3.1 - Compressive Response

It should be noted that the extent of the compression zone is not as critical as the size and extent of the cracks. Therefore, the use of the mean compressive concrete strength is adequate for crack width calculations. The mean modulus of elasticity of the reinforcing and prestressing steel and concrete is also considered adequate.

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For tension properties, the minimum yield strength of the reinforcing should be considered to maximize the crack width. Also, if tensile strength of the concrete is considered, the analysis should evaluate the 95th and 5th percentile concrete tensile strength limits. A more conservative approach would be to consider no tensile capacity of the concrete in the analysis.

2.4.3.3 - Temperature Effects on Material Properties

Improved material properties at low temperature, should not be used unless adequate cryogenic testing has been carried out to confirm these material properties. The variation of the mean coefficient of thermal expansion with temperature should also be considered in the solution.
2.5—Crack Width Calculations

The Code suggests that Eurocode EN Part 1 4.4.2.4, (4.80) be the basis for calculation of crack widths. In this approach crack width is determined from steel strains using the following relationship:

\[ w_k = \beta \bar{s}_m \varepsilon_{sm} \]  

where \( w_k \) is the 95th percentile crack width, \( \varepsilon_{sm} \) is the mean steel strain, \( s_m \) is the average final crack spacing and \( \beta \) is a design value that can be taken as:

- 1.7 for load induced cracking and for restraint cracking in section with minimum dimension in excess of 800 mm, or
- 1.3 for restraint cracking in sections with a minimum dimension depth, breadth or thickness, (whichever is the lesser) of 300 mm or less.

The average final crack spacing, \( s_m \), is computed from Eurocode 2 Part 1, 4.4.2.4 (4.82) as:

\[ s_m = 50 + 0.25k_1 k_2 \phi / \rho_r \]  

where:
- \( \phi \) is the bar size or average bar size in mm
- \( k_1 = 0.8 \) for high bond bars and 1.6 for plain bars
- \( k_2 \) is a coefficient which accounts for the form of the strain distribution and is between 0.5 for bending and 1.0 for pure tension.
- \( \rho_r \) is the effective reinforcing ratio, \( A_s / A_{c,eff} \), where \( A_s \) is the area of reinforcement contained within the effective tension area, \( A_{c,eff} \).

The mean strain value, \( \varepsilon_{sm} \), should be computed directly using the non-linear finite element model and considering all loads existing at the time of cracking. More specifically, the mean strain is obtained by averaging calculated strain over the length of steel that has exceeded the yield limit. In other words, for a single piece of reinforcing steel that has exceeded yield, \( \varepsilon_{sm} \) would be computed as the integrated strain over the length of the plastic zone of the reinforcing divided by the length of the plastic zone.

REFERENCES

1. ANSYS Inc., Canonsburg, PA
2. ABACUS, Inc., Providence, RI
3. ADINA R & D, Inc., Watertown, MA
4. Siemens PLM Software, Plano TX
5. EUROCODE 2 Design of concrete structures – Part 1 General rules and rules for buildings
CHAPTER 2—NOTATION AND TERMINOLOGY

thermal corner protection (TCP)—insulated and liquid tight system to protect the outer tank from thermal shock.

calculated crack width—crack width calculated using a concrete constitutive model defined in 8.1.1.7.

CHAPTER 6—MINIMUM PERFORMANCE REQUIREMENTS

6.3.2—Under spill conditions, the concrete above the thermal corner protection (TCP) should remain liquid tight, based upon minimum depths of compression and precompression.

6.3.4—Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness. The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.008 in. within the TCP embedment zone.

CHAPTER 8—ANALYSIS & DESIGN

8.1.1.7—Cracking and tension stiffening should be included by appropriate modification of the material stress strain relationship or by the use of finite elements that have the capability of cracking under R8.1.1.7—The Eurocode 2 is recommended for determining calculated crack widths. In this case, the calculated crack widths are characteristic and not mean calculated crack widths.
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Unless otherwise specified, the concrete constitutive mode from European Code should be used for determining calculated crack widths.

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However, it must be noted that calculated crack width represents an average numerical value that is not directly equivalent to calculated crack width measured in the field. Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.

Comment [LE88]: 076 Thompson

Comment is “Remove the last sentence from the Code Commentary:
“Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.”

Section R8.1.1.7 is text copied over from the Code and provided herein for the user’s benefit. Text must remain as-is to properly reflect the Code requirement. Changes to be addressed only if/once the Code has been changed accordingly.
Fig. A6(c)—Example of fixed-base full containment for LNG - Detail at foundation.
Material selection and material requirements used in the design of the 9% nickel-steel TCP and secondary bottom plates may be performed in accordance with API 620.

Comment found non-persuasive. Dealt with already elsewhere by deleting last sentence (Hoptay comment).

Part of Ref no. 021 - 2013.04.13 Minneapolis. Edit TN to use "anchors" rather than "bolts" or "studs" throughout.

Agree, revise as shown.

Agree in principle, but this is already addressed by requirement of analysis for thermal gradient. Future TN will define design conditions.

Revise last three sentences as shown.

017 and 018 Mash negative. Should be 5 locations, not 3 as shown. Revise as shown.

Comment is "Suggest inclusion of the words 'in the absence of a defined leak rate all intermediate levels shall be investigated. In practice this may be achieved by running a number spill levels to so as adequately bound the demands. Typically 5 levels may be used dividing the spill height into 4 equal units. In addition levels in close proximity to the TCP must be investigated.'"

No change. The response will be covered in the future TN on the design basis (DJ comment).

Comment is "Must be achieved through mechanical anchoring."
Anchor bolts (studs) should be placed in continuous (circumferential) rows along the concrete wall.

The concrete breakout strength of the anchor in tension should be checked per ACI 350 section D.5.2.
The pullout strength of the anchor in tension should be checked per ACI 350 section D.5.3.
The steel strength of the anchor in shear should be checked per ACI 350 section D.6.1.
The concrete breakout strength of the anchor in shear should be checked per ACI 350 section D.6.2.
The concrete pry-out strength of the anchor in shear should be checked per ACI 350 section D.6.3.
Interaction of tensile and shear forces should be checked per ACI 350 section D.7.
Agree, revise as shown.
(13/13 Wu, Pawski, Hoff, Berner, Howe, Hanskat, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

Page 8: [21] Comment [LE53]  rpawski  1/14/2014 3:42:00 PM
042 Pawski – Sat (superceded)

043 Jiang – delete as shown.
Sunday 3-18 - (11/11 Wu, Pawski, Hoff, Berner, Howe, Hjorteset, Hoptay, Garrison, Ballard, DJ, NKO)

Page 8: [22] Comment [LE54]  rpawski  1/14/2014 3:42:00 PM
044 & 047 Garrison negative – not resolved
044 Mash & 047 Jiang - Revise as shown.
Tue 3-20 - (3/3) Garrison, Ballard, Pawski
& Sun 3-19 - (12/12 Wu, Pawski, Hoff, Berner, Howe, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

045 Hoptay – withdrawn

Page 8: [23] Comment [LE55]  rpawski  1/14/2014 3:42:00 PM
049 Mash & Ballard negatives – not resolved
Agree, revise as shown.
Tue 3-20 - (3/3) Pawski, Garrison, Ballard)

Page 8: [24] Deleted  rpawski  3/31/2012 5:24:00 PM
non-linear FE material constitutive models
.

Page 8: [25] Comment [LE56]  rpawski  1/14/2014 3:42:00 PM
050 Jiang
Agree, revise as shown.
(11/11 Wu, Pawski, Hoff, Howe, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

Page 8: [26] Deleted  rpawski  1/13/2014 12:06:00 PM
. There are several commercially available FE programs that are adequate

Page 8: [27] Comment [LE57]  rpawski  1/14/2014 3:42:00 PM
078 Khalifa: Combine 1st two sentences pg 8 lines 32, 33 to read:
21-Oct-2013 Phoenix

Page 9: [28] Deleted  rpawski  3/31/2012 5:42:00 PM
This moment-curvature approach would only be suitable for consideration of the steady state
linear thermal gradient case and should also be used only for preliminary design.

Page 9: [29] Comment [LE60]  rpawski  1/14/2014 3:42:00 PM
055 Wu
Withdrawn Monday March 19.

056 Jiang
Revised as shown.
(13/13 Wu, Pawski, Hoff, Berner, Howe, Hanskat, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

057 & 058 Mash not addressed. Leave as is.
059 Jiang
Revise as shown.
(12/12 Wu, Pawski, Berner, Howe, Hanskat, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

060 Jiang
No change.
(13/13 Wu, Pawski, Hoff, Berner, Howe, Hanskat, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

Pg 9 line 24 Hoff: editorial
Change last sentence to read

062 Wu
Comment is “Change the word, “may” to “should”, since the reinforcing and pre-stressing steel need to be included in the nonlinear FEM cracking analysis in the liquid spill case.”

063 Mash
Comment is “Seems out of place in terms of the flow of the document.”

063 Oliver negative - not addressed
ACI 376 Technical Note on  
Thermal Corner Protection Design & Crack Analysis of the TCP Embedment Zone

Reported by ACI Committee 376

Concrete Structures for Refrigerated Liquefied Gas Containment

Neven Krstulovic-Opara*  
Chair

Piotr D. Moncarz  
Secretary

Junius Allen  
Alan D. Hatfield  
Thomas R. Howe  
Robert W. Nussmeier

Thomas A. Ballard*  
Humayun Hashmi  
Daiji Jiang  
Rolf P. Pawski*

Dale Berner  
Kare Hjorteset  
Jameel U. Khalifa  
Ramanujam S. Rajan

Mike S. Brannan  
George C. Hoff*  
Nicholas A. Legatos  
William E. Rushing

Hamish Douglas*  
Richard Hoffmann  
Praveen K. Malhotra  
Robert W. Sward

Jeffrey Garrison*  
John Holleyoak  
Keith A. Mash*  
Eric S. Thompson

Charles S. Hanskat  
Joseph M. Hoptay*  
Stephen W. Meier  
Sheng-Chi Wu

* Contributing Member

INTRODUCTION

ACI 376 provides requirements and some basic recommendations for the design of the Thermal Corner Protection (TCP) embedment zone. The purpose of this document Technical Note is to provide further guidance on-for (a) design and analysis of the TCP detailing and anchorage and (b) TCP liquid-tightness analysis in the TCP embedment zone (i.e., crack width calculations). The document therefore consists of two parts:
1. **Part 1 – Detailing & Construction Issues**: TCP detailing and related design issues are presented in the first part of this document.

2. **Part 2 – Crack Width for Liquid Tightness**: One of the key TCP-performance criteria is related to assuring adequate liquid tightness during a spill condition. ACI 376 Code specifies liquid tightness limits in terms of limiting concrete crack widths. The liquid tightness / crack width analysis procedure is presented in the second part of this document, followed by an example outlining proposed analysis steps that would meet ACI 376 Code requirements.

Although the code and this TN do not explicitly define leak tightness criteria for the anchorage and embeddment, the design and construction of these components should be carried out with the clear objective of protecting the corner joint from product temperatures.
CONTENTS

INTRODUCTION

CHAPTER 1 – TCP DESIGN
1.1—General
1.2—Embedment Plate and Anchorage Studs

CHAPTER 2 – LIQUID TIGHTNESS AND CRACK WIDTH ANALYSIS
2.1—General
2.2—Analysis Procedure
2.3—Numerical Model
2.4—Material Constitutive Models
2.5—Crack Width Calculations

APENDICES

APENDIX A – ACI 376 TCP CODE REQUIREMENTS

REFERENCES
CHAPTER 1 – TCP Design

Figure 1.1: Thermal Corner Protection (TCP) Detail

1.1—General

The thermal corner protection (TCP) is an insulated and liquid tight system located at the bottom of the outer secondary concrete wall, as shown in Figure 1.1 a. The primary function of TCP is to protect already highly stressed wall to slab joint from additional thermal loads during spill conditions. The TCP is designed to provide both (a) a liquid and (b) a thermal barrier at the wall to slab joint, thus protecting the joint from exposure to cryogenic temperatures during a spill condition.

The TCP is connected to a secondary bottom plate that provides a liquid barrier above the slab, as shown in Figure 1.1 a. The TCP is attached to the concrete wall through an embedment plate located at the top of the TCP, as shown in Figure 1.1 b. During the spill condition, the concrete wall above the TCP, the TCP and TCP embedment will be subjected to significant thermal and mechanical loads. The TCP embedment should be designed to remain intact and in place during the spill condition.
The concrete wall above the TCP, directly exposed to spilled product, should remain liquid tight and substantially vapor tight during the spill condition. This is assured by maintaining a compression zone in the wall exposed to the spill and by limiting cracking, crack width on the inside face of the wall in the vicinity of the TCP embedment zone plate during a spill.

The scope of this section is to provide guidelines and best practices for the detailing of the TCP region, i.e., the TCP, the TCP embedment plate and TCP embedment plate anchorage to the outer concrete wall. Information is provided for the evaluation of the embedment plate, design of the anchor studs, and attachment to the concrete wall, and for the evaluation of cracking in the embedment zone. Material selection and material requirements used in the design of the 9% nickel steel TCP and secondary bottom plates may be performed in accordance with API 620.

1.2—Embedment Plate and Anchor Studs Anchors

The TCP embedment plate should be designed to resist radial and vertical loads and moments resulting from both (a) thermal gradients, as well as (b) mechanical forces that develop during a spill condition including SSE-AFT.

The TCP design consists of the following steps:

1.2.1 - STEP 1: TCP Load Definition

- Finite element analyses are performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment will be subjected to including [thermal], prestress, creep, concrete shrinkage, internal pressure, hydrostatic pressure and hydrodynamic pressure due to seismic aftershock (SSE-AFT). Starting Initial temperatures and conditions should be selected so as to maximize the demand under consideration. For instance for the design of the anchors, the critical condition is likely to be warm wall (summer) and a cold checking thermal shock to the embedment—Whereby, thereby creating maximum straining across the section.

- Various spill levels should be considered to determine the most severe effect on the embedment and concrete wall. This should include spill levels—a spill level located just below the top of the TCP which will place the largest temperature differential between the TCP and the concrete wall as well as various. A minimum of three levels should be considered for spill levels above the TCP, up to the 1) at top of the TCP embedment zone, 2) at mid-height, and 3) at full spill level.
The analysis should be based on both steady state and transient conditions, as specified in ACI 376 Code section 8.4.8. R8.4.8 specifically indicates that during transient conditions an embedment such as the TCP will frequently experience the greatest self-straining forces.

1.2.2 - STEP 2: Embedment Plate Design

- The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall or by other suitable means (e.g., studs). Anchor bolts (studs) should be placed in continuous (circumferential) rows along the concrete wall.
- The embedment plate should be anchored with circumferential studs a minimum of two rows of circumferential stud anchors should be used to anchor the embedment plate. The spacing between mechanical anchors (studs) should be limited to ensure that the axial, bending and shear stresses in the embedment plate are within the allowable stress limit anchors have significant impact on the TCP embedment performance and thus should be considered in design.
- Embedment plate and mechanical anchor material as well as the TCP material should be suitable for the product temperature.
- Allowable stresses i.e., material selection and material requirements used in the design of the embedment plates may be selected in accordance with API 620.
- Anchor spacings should be selected so as to be multiples of the bar spacing to enable a clash-free design.

1.2.3 - STEP 3: Anchor Bolt Anchorage Design

The mechanical anchorage (anchors, bolts or studs) and concrete at the anchor location should meet the requirement for anchoring to the concrete wall defined in the ACI 350 Appendix D.

- The steel strength of the anchor in tension should be as per ACI 350 section D.5.4.
- The concrete breakout strength of the anchor in tension should be checked per ACI 350 section D.5.2.
- The pullout strength of the anchor in tension should be checked per ACI 350 section D.5.3.
- The steel strength of the anchor in shear should be checked per ACI 350 section D.6.4.
- The concrete breakout strength of the anchor in shear should be checked per ACI 350 section D.6.2.
- The concrete pullout strength of the anchor in shear should be checked per ACI 350 section D.6.3.
- Interaction of tensile and shear forces should be checked per ACI 350 section D.7.

1.2.4 - STEP 4: Liquid Tightness

Liquid tightness at the embedment plate should be considered in the details and design of the anchorage as defined by the owner.

Note - consensus at 2013.10.21 Phoenix meeting was new “1.2.4 Step 4” is not needed and should be deleted in its entirety. Shown for information and to be deleted.
CHAPTER 2 – PART 2: Liquid Tightness and Crack Width Analysis

2.1—General

When subjected to the spill condition, the secondary concrete wall will be loaded with high forces thermally induced and mechanical forces. These forces due to mechanical loads and thermal effects that will lead to significant wall cracking. During the spill condition, integrity of the concrete wall must be maintained. As specified in the ACI 376 Code, the wall should remain liquid and substantially vapor tight.

More specifically:

1) ACI 376 section 6.3.3: “Unless a leak-tight membrane/liner has been used, a minimum portion of the concrete should remain in compression in accordance with the following:
   a) A compressive zone of either 10% of the section thickness or 3.5 in., whichever is greater, should be provided; and
   b) A minimum average compressive stress within the compressive zone of 145 lb/in^2 should be maintained.”

2) ACI 376 section 6.3.4: “Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness. The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.008 in. within the TCP embedment zone. Recommendations for crack width calculations are provided in 8.1.1.8.”

3) ACI 376 section 8.1.1.8 - requires that the cracks widths should be calculated as characteristic and not mean crack widths as per EN 1992-1-1.

Non-linear finite element analysis should be performed to ensure that these requirements are met.

2.2—Analysis Procedure

The analysis procedure consists of the following steps:

2.2.1 - STEP 1: Thermal Analysis

Thermal analysis is performed based on a thermal model using Finite Element or Finite Difference approach. Steps include:

1) Modeling including specific tank geometry and material thermal properties

2) Thermal boundary condition definition/application to equilibrium
3) Application of LNG RLG\textsuperscript{spill or external fire} temperature loads obtained by considering rate of leakage into annular space and exposed to transient temperatures.

4) Continue analysis until steady state final temperatures are reached; temperature distribution is obtained.

5) Repeat for all thermal load cases.

2.2.2 - STEP 2: Structural Analysis

Structural Analysis is performed \textit{based on the stress model} using the Finite Element approach. Steps include:

1) \textbf{Modeling}
2) \textbf{To establish initial conditions, apply dead load, prestressing, normal operating thermal} and any other steady state load, then \textbf{iterate to equilibrium}
3) \textbf{Check crack width}

4) \textbf{Apply LNG RLG spill temperature transients} and \textbf{iterate to equilibrium}

5) \textbf{Compute Beginning with the initial condition defined in step 2, compute crack widths at time-steps throughout the transient where reinforcing strains are the greatest and exceed the material yield strength. Furthermore, at each time step determine the adequacy of the compression zone.}

6) \textbf{Repeat for all thermal load cases}

2.3—Numerical Model

Calculation of cracking and crack widths for the LNG RLG spill condition and/or external fire condition shall be performed using a rational engineering analysis. Both linear or non-linear finite element (FE) analysis should be used as discussed in 2.3.1 and 2.3.2.

2.3.1 Non-Linear FE Analysis

In this case a non-linear finite element program is used in conjunction with:

- non-linear FE material constitutive models Implementing the non-linear material constitutive relationship for concrete and steel, and
- Carrying out FE analysis to obtain stress/strain contours, and
- Performing FE analysis post process to calculate characteristic crack width calculations as per following a method such as Eurocode EN 2 1992-1-1 (see section 2.5 in this TN).

Either a proprietary or one of several commercially available FE programs can be used. There are several commercially available FE programs that are adequate for performing this calculation. A few of more widely

\begin{itemize}
\item Agreement by: (superceded)
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\item Agreement by: (superceded)
\end{itemize}
used non-linear FE programs available in the United States include ANSYS\textsuperscript{1}, ABACUS\textsuperscript{2}, ADINA\textsuperscript{3} and NASTRAN\textsuperscript{4}. There are also many proprietary FE programs that have been designed specifically to consider the cracking problem for reinforced concrete containment structures.

### 2.3.2 Linear-Simplified FE Analysis

**Linear-Simplified FE analysis** is usually used only in the preliminary design. Two possible approaches include:

**a) Reduced-Stiffness / Cracked-Section Approach:** The calculation is performed using a linear finite element analysis where the reduction in stiffness due to cracking is considered. However, it should be noted that this is a very time consuming process and is thus usually only used in the preliminary design.

**b) Moment-Curvature Approach:** The moment curvature response properties are obtained using a concrete section analysis program by implementing in conjunction with:

- non-linear stress-strain material properties, and
- a non-linear shell formulation that accounts for the cracking induced stiffness redistribution.

This moment-curvature approach would only be suitable for consideration of the steady state linear thermal gradient case and should also be used only for preliminary design.

### 2.3.3 Mesh Type and Size

The linear or non-linear FE model will usually be axisymmetric or a small slice 3D model of the containment for consideration of the general case of a symmetric LNG-RLG spill loads and a larger sector separate model for consideration of the LNG-RLG spill case where non-axisymmetric discontinuities are considered.

Typically, the structural model contains a fine-mesh or a high density of solution points. The model includes the base slab, foundation springs, containment wall, roof structure and local discontinuities, such as the prestressing buttresses. If the liners are considered as structural members, then liners should be included if they are considered as structural members.

A more detailed substructure model of the region above the TCP anchorage might be considered in order to reduce the computational demand, provided it can be demonstrated that the boundary conditions and loadings correctly represent the global model.

The reinforcing and prestressing steel should also be modeled and the prestressing forces applied as part of the loading or construction sequence.

### 2.3.4 Loading
The LNG-RLG spill case should include hydrostatic pressure from the LNG-RLG fluid in the annular space. Dead load, live load and steady state temperatures coincident prior to the LNG-RLG spill, shall be applied prior to application of the temperature transients.

Nodal temperature transients will typically be computed in a separate heat transfer finite element or finite difference solution. The thermal model used for determining nodal temperatures is a high density model which should include concrete foundation, soil thermal boundary condition, walls, roof and outside or inside ambient temperature boundary conditions. This model should also include the base slab insulation and the thermal corner protection insulation.

### 2.3.5 Heat Thermal Analysis

The heat transfer analyses should consider both maximum (95\textsuperscript{th} percentile) and minimum (5\textsuperscript{th} percentile) ambient temperatures. The LNG-RLG spill is applied internally to the containment and the adjacent tank fire case is applied externally. The LNG-RLG spill load case should also include the vapor temperature generated from the spill above the liquid level. Nodal temperature time histories are computed and mapped to the structural finite element model. The concrete wall internal temperatures from the thermal model are also typically used to determine the selection and placement of normal (A615), cold temperature (A706) and cryogenic reinforcing complying with the requirements of ACI 376.

The LNG-RLG hydrostatic pressure and temperature time histories are applied gradually and the iterative solution computes concrete stresses and strains, crack locations and reinforcing stresses.

### 2.4—Material Constitutive Models

#### 2.4.1 Concrete Constitutive Model

Recognized concrete constitutive models should be used in the analysis. Examples include material models described by Eurocode 2\textsuperscript{5} and shown in the Figure 2.1 below. The concrete constitutive model should also account for reduction in tensile stiffness after cracking of concrete including the effects of tension stiffening linear tension stiffness effects with tension failure or reduction in stiffness at the cracking strain of the concrete.

**Figure 2.1:** Stress-Strain Diagram for Uniaxial Compression from Eurocode EN 2, 1992-1-1
The $\sigma_c - \varepsilon_c$ material relationship shown in Figure 2.1 is taken from Eurocode EN 2 Part 1.4.2.1.3.1 (4.1).

For short term loading the relationship is defined as:

$$\frac{\sigma_c}{f_c} = \frac{(k \cdot n - n^2)}{[1 + n \cdot (k-2)]}$$ (1)

where:

- $f_c$: concrete compressive strength at 28 days (N/mm$^2$) < 0.0 (2)
- $\varepsilon_{cu}$: ultimate strain < 0.0 (3)
- $n = \varepsilon_c/\varepsilon_{c1}$ (both < 0.0) (4)
- $k = (1.1E_{c,nom})\varepsilon_{c1}/f_c$ (5)
- $E_{c,nom} = E_{cm}/\gamma_c$ (kN/mm$^2$) (6)
- $\gamma_c$: partial safety factor = 1.5 unless justified by adequate control procedures. (8)
- $E_{cm} = 9.5(f_c + 8)^{1/3}$ (E$_{cm}$ in kN/mm$^2$; $f_c$ in N/mm$^2$) (9)

The tension side of the $\sigma_c - \varepsilon_c$ material relationship may be taken as:

$$\sigma_c = E_{cm}\varepsilon_c$$ (N/mm$^2$) for $\sigma_c < f_{ctm}$ (10)

$$\sigma_c = 0$$ for $\sigma_c > f_{ctm}$ (11)

where:

$$f_{ctm} = 0.30f_{c}^{2/3}$$ (N/mm$^2$) (13)

In reality, the tension tension softening is usually introduced following rupture of the concrete in order to provide for numerical stability in the solution.

2.4.2 Steel Constitutive Models
Figure 2.2 shows a typical uniaxial stress strain curve for reinforcing steel and Figure 2.3 a typical uniaxial stress-strain curve for prestressing steel.

**Figure 2.2:** Typical Uniaxial Stress-Strain Curve for Reinforcing Steel from Eurocode EN 2 1992-1-1

**Figure 2.3:** Typical Uniaxial Stress-Strain Curve for Prestressing Steel from Eurocode EN 2 1992-1-1

Other concrete and steel constitutive models may be used provided it can be demonstrated that these models accurately characterize material behavior.

### 2.4.3 Selection of Material Parameter Values

Since the LNG-RLG spill case, it is critical that cryogenic liquid be prevented from migrating behind the TCP, and conservative assumptions should be used when selecting material properties.

#### 2.4.3.1 - Compressive Response

It should be noted that the extent of the compression zone is not as critical as the size and extent of the cracks. Therefore, the use of the mean compressive concrete strength is adequate for crack width calculations. The mean modulus of elasticity of the reinforcing and prestressing steel and concrete is also considered adequate.

#### 2.4.3.2 - Tensile Properties

For tension properties, the minimum yield strength of the reinforcing should be considered to maximize the crack width. Also, if tensile strength of the concrete is considered, the analysis should evaluate the 95<sup>th</sup> and 5<sup>th</sup> percentile concrete tensile strength limits. A more conservative approach would be to consider no tensile capacity of the concrete in the analysis.
2.4.3.3 - Temperature Effects on Material Properties

Improved material properties at low temperature, should not be used unless adequate cryogenic testing has been carried out to confirm these material properties. The variation of the mean coefficient of thermal expansion with temperature should also be considered in the solution.

2.5—Crack Width Calculations

The Code suggests that Eurocode EN 2 Part 1 4.4.2.4, (4.80) be the basis for calculation of crack widths. In this approach crack width is determined from steel strains using the following relationship:

\[
\omega_k = \beta s_{rm} \varepsilon_{sm}
\]

where \(w_k\) is the 95th percentile crack width, \(\varepsilon_{sm}\) is the mean steel strain, \(s_{rm}\) is the average final crack spacing and \(\beta\) is a design value that can be taken as:

- 1.7 for load induced cracking and for restraint cracking in section with minimum dimension in excess of 800 mm, or
- 1.3 for restraint cracking in sections with a minimum dimension depth, breadth or thickness, (whichever is the lesser) of 300 mm or less.

The average final crack spacing, \(s_{rm}\), is computed from Eurocode 2 Part 1, 4.4.2.4 (4.82) as:

\[
s_{rm} = 50 + 0.25k_2 k_1 \phi / \rho_r
\]

where:

- \(\phi\) is the bar size or average bar size in mm
- \(k_1 = 0.8\) for high bond bars and 1.6 for plain bars
- \(k = 0.8\) for tensile stresses that are due to intrinsic deformations
- \(k_2\) is a coefficient which accounts for the form of the strain distribution and is between 0.5 for bending and 1.0 for pure tension.
- \(\rho_r\) is the effective reinforcing ratio, \(A_s/A_{c,eff}\), where \(A_s\) is the area of reinforcement contained within the effective tension area, \(A_{c,eff}\)

The mean strain value, \(\varepsilon_{sm}\), should be computed directly using the non-linear finite element model and considering all loads existing at the time of cracking. More specifically, the mean strain is obtained by averaging calculated strain over the length of steel that has exceeded the yield limit. In other words, for a single piece of reinforcing steel that has exceeded yield, \(\varepsilon_{sm}\) would be computed as the integrated strain over the length of the plastic zone of the reinforcing divided by the length of the plastic zone.
REFERENCES

1. ANSYS Inc., Canonsburg, PA
2. ABACUS, Inc., Providence, RI
3. ADINA R & D, Inc., Watertown, MA
4. Siemens PLM Software, Plano TX
5. EUROCODE 2 Design of concrete structures – Part 1 General rules and rules for buildings
Appendix A: ACI 376 Code TCP Requirements

CHAPTER 2—NOTATION AND TERMINOLOGY

thermal corner protection (TCP)—insulated and liquid tight system to protect the outer tank from thermal shock.

calculated crack width—crack width calculated using a concrete constitutive model defined in 8.1.1.7.

CHAPTER 6—MINIMUM PERFORMANCE REQUIREMENTS

6.3.2—Under spill conditions, the concrete above the thermal corner protection (TCP) should remain liquid tight, based upon minimum depths of compression and precompression.

6.3.4—Calculated crack widths should be considered at TCP embedment when cracking would result in liquid product migrating behind the TCP and compromising its effectiveness.

The embedment zone should extend a minimum of two times the wall thickness above the TCP anchorage. Calculated crack widths should not exceed 0.004 in. within the TCP embedment zone.

CHAPTER 8—ANALYSIS & DESIGN

8.1.1.7—Cracking and tension stiffening should be included by appropriate modification of the material stress strain relationship or by the use of finite elements that have the capability of cracking under 

R8.1.1.7—The Eurocode 2 is recommended for determining calculated crack widths. In this case, the calculated crack widths are characteristic and not mean calculated crack widths.
tension, and crushing under compression as well as the ability to include reinforcing steel.

Unless otherwise specified, the concrete constitutive mode from European Code should be used for determining calculated crack widths.

Extensive field experience with liquid retaining and offshore concrete structures has demonstrated that satisfactory liquid tightness and liquid retaining performance can be achieved by imposing calculated crack width limits.

However, it must be noted that calculated crack width represents an average numerical value that is not directly equivalent to calculated crack width measured in the field. Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.

Comment [LE88]: 076 Thompson

Comment is “Remove the last sentence from the Code Commentary: “Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.””

Section R8.1.1.7 is text copied over from the Code and provided herein for the user’s benefit. Text must remain as-is to properly reflect the Code requirement. Changes to be addressed only if/once the Code has been changed accordingly.
Fig. A.6(c)—Example of fixed-base full containment for LNG - Detail at foundation.
025 Wu
Revise 1.2.3 as shown and as new section 1.2.4 as shown.
(9/9) Wu, Pawski, Howe, Hoff, Hoptay, Garrison, Ballard, Brannan, NKO)
2013.10.21 Phoenix – consensus was new section 1.2.4 is not needed and should be deleted in its entirety.

042 Pawski – Sat (superceded)

043 Jiang – delete as shown.
Sunday 3-18 - (11/11 Wu, Pawski, Hoff, Berner, Howe, Hjorteset, Hoptay, Garrison, Ballard, DJ, NKO)

044 & 047 Garrison negative – not resolved
044 Mash & 047 Jiang - Revise as shown.
Tue 3-20 - (3/3) Garrison, Ballard, Pawski
& Sun 3-19 - (12/12 Wu, Pawski, Hoff, Berner, Howe, Hjorteset, Hoptay, Garrison, Ballard, DJ, Brannan, NKO)

045 Hoptay – withdrawn
## Technical Note on TCP (TCP – TN)

**Approved Sections**
- Section Approved with Comments to be resolved
- Negative Vote

**Last Update:** 4 / 13 / 2013 - 376-D meeting in Minneapolis

**2013.04.13 376-C Minneapolis**

### Members that Voted

<table>
<thead>
<tr>
<th>Voting Members that voted (79%)</th>
<th>18. Nussmeier, Robert W</th>
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<tbody>
<tr>
<td>1. Hjorteset, Kare</td>
<td>11. Jiang, Daju</td>
</tr>
<tr>
<td>2. Brannan, Mike S</td>
<td>20. Pawski, Rolf P</td>
</tr>
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<td>5. Garrison, Jeffrey</td>
<td>23. Hanskat, Charles S</td>
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<td>7. Hoff, George C</td>
<td>25. Hashmi, Humayun</td>
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<td>17. Moncarz, Piotr D</td>
<td>27. Sward, Robert</td>
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<tr>
<td>15. Mahotra, Praveen</td>
<td>28. Thompson, Eric</td>
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### Members Attending:

- 2013.04.13 – 376 D Minneapolis

<table>
<thead>
<tr>
<th>Members Attending</th>
<th>1. Brannan, Mike</th>
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<tbody>
<tr>
<td>2. Hjorteset, Kare</td>
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<td>8. Khalifa, Jameel</td>
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<td>26. Rajan, Ramanujam S</td>
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<td>28. Thompson, Eric</td>
<td>29. Hoff, George</td>
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### 2014.01.08 TCP text negatives requiring discussion:

- Ref. no. 1, Comment 6 - Ballard proposed addition to Introduction

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Text</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I am not sure the TCP can be constructed as detailed because it would be impossible to weld both sides of the TCP plate to the embedment plate. It would also be better to radius the sharp corner shown on the TCP plate. Would it be possible to simply lap weld the TCP plate to the embedment plate? Should the embedment zone also extend 2X the wall thickness below the embedment plate?</td>
<td>Brannan</td>
</tr>
</tbody>
</table>

### Suggested Change

- **INTRODUCTION:**

  ACI 376 provides requirements and some basic recommendations for the design of the Thermal Corner Protection (TCP) embedment zone. The purpose of this technical note document is to provide further guidance on (a) design and analysis of the TCP embedment anchorage detailing and (b) TCP liquid-tightness analysis (i.e., crack width calculations) in the TCP embedment zone (i.e., crack width calculations).

  Update title to read: **Thermal Corner Protection Design & Crack Analysis**

Agree with comment – Hoffman

With Respect to M. Brannan’s Comments, it is my opinion this can be welded from both sides, by making this attachment weld first and then going on with the construction. There will be a “fill-in plate that is required to build up the TCP side wall.

I have no objection to the proposed changes.
### 1<sup>st</sup> Ballot Results (Approved w. Comment)

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Text</th>
<th>Author</th>
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<tbody>
<tr>
<td>8</td>
<td>Page 5, line 2, item 3</td>
<td>Mash</td>
<td>Suggest rewording and removing ‘substantially’ link to definitive acceptance criterion to avoid confusion. Suggest exact acceptance criterion words such as - under the spillage condition the crack widths on the inside face shall be limited to xx, compressive stresses in both the meridional and vertical directions shall be minimum y, max z, The comment found partially persuasive. Limiting values are covered in the Code (e.g., compressive zone size, crack width limits, etc.) and do not need to be repeated here. Revise text for clarity to read: “The concrete wall above the TCP, directly exposed to spilled product, should remain liquid and substantially vapor tight during the spill condition. This is assured by maintaining a compression zone in the wall exposed to the spill and by limiting the crack width cracking on the inside face of the wall in the vicinity of the TCP embedment plate zone during a spill.”</td>
</tr>
</tbody>
</table>

### 2<sup>nd</sup> Ballot Results

#### 2<sup>nd</sup> BALLOT: RESPONSE being BALLOTED

<table>
<thead>
<tr>
<th>Voting Member’s VOTE &amp; COMMENTS</th>
<th>Suggested Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disagree - Ballard</td>
<td>I believe the embedment zone should extend at least to the bottom of the TCP plate since migration of cracks in this zone would compromise the leak tightness of the detail. NOTED in Fig 1.1(b). 2013.04.13 – 376-C Minneapolis: Agreed and that Tom Ballard to propose wording. From TB email dated 2013.04.15: “Although the code and this TN do not explicitly define leak tightness criteria for the anchorage and embedment, the design and construction of these components should be carried out with the clear objective of protecting the corner joint from product temperatures.” Note – added to Introduction on pg 2.</td>
</tr>
<tr>
<td>Agree – Jiang, Moncarz, Hoff, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
<td>Agree with editorial changes – Khalifa, Roetzer, Krstulovic</td>
</tr>
<tr>
<td>The comment found persuasive. Change text to read: “Material selection and material requirements used in the design of the 9% nickel steel TCP and secondary bottom plates may be performed in accordance with API 620.”</td>
<td>2013.04.13 – 376-C Minneapolis: Agree with comment. Note – This sentence is deleted based on Comment LE 15 in text markup.</td>
</tr>
</tbody>
</table>

<p>| 10 | Page 5 Line 10 | Hoptay | The material selection is temperature dependent and to state that the TCP is 9% Ni infers an LNG tank and not RLG tanks in general. The comment found persuasive. Change text to read: “Material selection and material requirements used in the design of the 9% nickel steel TCP and secondary bottom plates may be performed in accordance with API 620.” | Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic |</p>
<table>
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<tr>
<th>Ref No.</th>
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<th>Author</th>
<th>Comments</th>
<th>2nd Ballot Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Page 5, line 4, item 6</td>
<td>Mash</td>
<td>Assurance is through cracks + compression zones not through cracks alone. Crack width limitation in the vicinity of the embed is to prevent liquid migration behind the TCP area.</td>
<td>No action. Covered in previous response.</td>
</tr>
<tr>
<td>13</td>
<td>P. 5, Line 15</td>
<td>Wu</td>
<td>add “seismic Aftershock load”</td>
<td>The comment found persuasive. Change text to read: &quot;The TCP embedment plate should be designed to resist radial and vertical loads and moments resulting from both (a) thermal gradients, as well as (b) mechanical forces that develop during a spill condition including SSE. The TCP design consists of the following steps:&quot;</td>
</tr>
<tr>
<td>15</td>
<td>Page 5, line 21, item 10</td>
<td>Mash</td>
<td>Starting temperatures and conditions should be selected so as to maximise the demand under consideration. For instance for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking to the embed. Whereby creating maximum straining across the section.</td>
<td>The comment found persuasive. Add proposed text to line 22:</td>
</tr>
</tbody>
</table>

### Suggested Change

<table>
<thead>
<tr>
<th>2nd Ballot Results</th>
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</thead>
<tbody>
<tr>
<td>2013.04.13 – 376-C Minneapolis:</td>
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<tr>
<td>2013.04.13 – 376-C Minneapolis:</td>
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<table>
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<tr>
<th>Voting Member’s VOTE &amp; COMMENTS</th>
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</table>
### 1st Ballot Results (Approved w. Comment)

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</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>P.5, Line 22, at the end of the paragraph</td>
<td>Wu</td>
</tr>
</tbody>
</table>

Add “and hydrodynamic pressure due to seismic aftershock”.

### 2nd Ballot Results

**2ND BALLOT: RESPONSE being BALLOTED**

<table>
<thead>
<tr>
<th>Voting Member’s VOTE &amp; COMMENTS</th>
<th>Suggested Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agree with editorial changes - Pawski</td>
<td>Starting temperatures and conditions should be selected so as to maximize the demand under consideration. For instance, for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking thermal shock to the embed. Thereby creating maximum straining across the section.</td>
</tr>
<tr>
<td>Agree with editorial changes - Douglas</td>
<td>Pawski 2013.04.23 – Allen comment below shown incorrectly as Douglas and deleted here. Correct comment is: &quot;... cold shock to the embed which results in the maximum strain across the section.&quot;</td>
</tr>
<tr>
<td>Douglas additional comment at end of Ballot Summary:</td>
<td>&quot;1. Page 5, Para 1.2.1 Line 24: Also Comment LE27: What is the advantage of the use of the term &quot;demand&quot; as opposed to load? If a new term is to be introduced then it's use must be defined: When is a load a demand?&quot;</td>
</tr>
<tr>
<td>Agree with editorial changes - Allen</td>
<td>For instance for the design of the anchors the critical condition is likely to be warm wall (summer) and cold shocking to the embed. Thereby creating maximum straining across the section.</td>
</tr>
</tbody>
</table>
| Agree with changes - Oliver | "Finite element analyses is performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment will be subjected to including thermal, prestress, creep, concrete shrinkage, internal pressure, hydrostatic pressure and hydrodynamic pressure due to seismic aftershock (SSE, aft)."

The comment found persuasive. Change text to read:

- “Finite element analyses is performed first to determine forces resulting from thermal gradients applied to the TCP, TCP embedment plate and outer concrete wall. Loads should include all loads that the TCP and the embedment will be subjected to including thermal, prestress, creep, concrete shrinkage, internal pressure, hydrostatic pressure and hydrodynamic pressure due to seismic aftershock (SSE, aft).”

Agree – Jiang, Moncarz, Hoff, Rushing, Hoffman, Humayun, Howe, Wu, Ballaard, Malhotra, Garrison, Mash, Allen, Legatos, Widianto, Hoptay, Oliver, Pawski, Hatfield, Braman, Kristulovic.

Agree with editorial change – Khalifa, Douglas, Roetzer, Kristulovic.
### 1st Ballot Results (Approved w. Comment)

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<th>Ref No.</th>
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<tbody>
<tr>
<td>18</td>
<td>Page 5, line 28, item 12</td>
<td>Mash</td>
</tr>
</tbody>
</table>

**Suggest inclusion of the words 'in the absence of a defined leak rate all intermediate levels shall be investigated. In practice this may be achieved by running a number of spill levels to so as adequately bound the demands. Typically 5 levels may be used dividing the spill height into 4 equal units. In addition levels in close proximity to the TCP must be investigated.'**

**Agree in principle with comment. Revise as noted and address spill levels in a future edition of the Code.**

- "Various spill levels should be considered to determine the most severe effect on the embedment and concrete wall. This should include a spill level located just below the top of the TCP which will place the largest temperature differential between the TCP and the concrete wall. Also a minimum of three levels should be considered for spill levels above the TCP up to the top of the TCP embedment zone at mid-height, and full spill height." **Agree – Jiang, Moncarz, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Allen, Legato, Widianto, Roetzer, Hatfield, Brannan, Krstulovic**

| 20      | Page 5, line 32, item 14 | Mash |

**Must be achieved through mechanical anchoring!**

**The comment found persuasive. Revise to read:**

"The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall **mechanically anchored**. Anchor bolts should be placed in continuous (circumferential) rows along the concrete wall."

**Agree – Jiang, Moncarz, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Mash, Douglas, Allen, Legato, Widianto, Oliver, Pawski, Hatfield, Brannan, Oliver, Pawski, Hatfield, Brannan, Allen, Malhotra, Garrison, Humayum, Wu, Ballard, Allen, Legato, Widianto, Jenkins, Ross, Olafson, Krstulovic"
### 1st Ballot Results (Approved w. Comment)

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<tbody>
<tr>
<td>21</td>
<td>Page 6, line 1, item 1</td>
<td>Mash</td>
</tr>
</tbody>
</table>

### 2nd Ballot Results

#### 2nd BALLOT: RESPONSE being BALLOTED

<table>
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<tbody>
<tr>
<td>6</td>
<td>Krstulovic</td>
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#### Voting Member’s VOTE & COMMENTS

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<tbody>
<tr>
<td>6</td>
<td>Delete second sentence completely as the same is essentially said in the next sentence. “The TCP embedment plate should be cast in place and mechanically anchored to the concrete wall. Anchor studs should be placed in continuous (circumferential) rows along the concrete wall.”</td>
</tr>
<tr>
<td>2013.04.13 – 376-C Minneapolis:</td>
<td>After discussion it was agreed delete second sentence as suggested.</td>
</tr>
<tr>
<td>6</td>
<td>Agree with suggested change -Khalifa, Roetzer</td>
</tr>
<tr>
<td>6</td>
<td>Modify last sentence: “Anchor studs should be welded in continuous circumferential rows along the embed plate.”</td>
</tr>
<tr>
<td>2013.04.13 – 376-C Minneapolis:</td>
<td>Withdrawn after discussion on deleting second sentence as per Khalifa, Roetzer, and Hoptay.</td>
</tr>
<tr>
<td>6</td>
<td>Disagree -Hoptay</td>
</tr>
<tr>
<td>2014.01.08 TCP text - negative is resolved</td>
<td>Delete second sentence because next sentence covers the same information</td>
</tr>
<tr>
<td>2013.04.13 – 376-C Minneapolis:</td>
<td>After discussion it was agreed delete second sentence as suggested.</td>
</tr>
<tr>
<td>6</td>
<td>Agree – Jiang, Moncarz, Hoff, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Garrison, Mash, Douglas, Allen, Legates, Widianto, Hoptay, Roetzer, Oliver, Hatfield, Krstulovic</td>
</tr>
<tr>
<td>6</td>
<td>Agree with comments -Pawski</td>
</tr>
<tr>
<td>6</td>
<td>Bullet points 1 &amp; 2 should be combined</td>
</tr>
<tr>
<td>6</td>
<td>Use “studs” or “bolt studs” consistently</td>
</tr>
<tr>
<td>6</td>
<td>Agree - Brannan</td>
</tr>
</tbody>
</table>

### The comment found persuasive. Revise to read as noted below. Address questions on spacing and gap size in future:

> The TCP embedment plate should be anchored with circumferential stud rows. When the embedment plate should be anchored with circumferential studs, a minimum of two rows of circumferential studs should be used to anchor the embedment plate. The spacing between mechanical anchors has significant impact on the TCP embedment performance and thus should be considered in the design. It should be limited to ensure that the axial, bending and shear stresses in the embedment plate are within the allowable stresses.

**2014.01.08 TCP text negative requiring discussion:**

> ~ Comment 27 – number of locations 5 or 3

Note that our Figure 1a shows four rows of circumferential studs. Should it show two rows of studs in solid line ink and the other two in shaded or dashed ink to indicate the potential for using more than two rows?
### 1st Ballot Results (Approved w. Comment)

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### 2nd Ballot Results

#### 2nd BALLOT: RESPONSE being BALLOTTED

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<tbody>
<tr>
<td>2013.04.13 – 376-C Minneapolis: Agree, annotate sketch to state “2-rows minimum.”.</td>
<td></td>
</tr>
<tr>
<td>Also recommend deleting bolts from first line under section 1.2.3</td>
<td></td>
</tr>
</tbody>
</table>

### 2nd Ballot Results

#### 2013.04.13 – 376-C Minneapolis: Agree with editorial changes - Khalifa

<table>
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<tr>
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#### 2013.04.13 – 376-C Minneapolis: “Anchors” to be used throughout. Edit TN and replace bolts & studs with “anchors.”

<table>
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<tr>
<th>Author</th>
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</table>

#### 2013.04.13 – 376-C Minneapolis: Disagree – Hoptay

<table>
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#### 2014.01.08 TCP text - negative is resolved

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#### 2013.04.13 – 376-C Minneapolis: Persuasive, use proposed wording.

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### NEW

#### Page 6 Para 1.2.4

<table>
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<tr>
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</tbody>
</table>

### 28 Page 7, line 11, item 1

<table>
<thead>
<tr>
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<th>Comments</th>
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<tbody>
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<td></td>
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</tbody>
</table>

### Notes

- **Note – consensus at 2013.10.21 Phoenix meeting was to delete the new section 1.2.4**
- **Note – Mash negative resolved**

Worded incorporated into 2014.01.08 TCP markup is essentially as suggested by Mash, as follows:

During the spill condition, the secondary concrete wall will be subjected to large forces due to mechanical loads and thermal effects that will lead to significant wall cracking. Integrity of the concrete wall must be maintained. As specified in the ACI 376 Code, the wall should be designed to maintain its structural integrity through the appropriate selection of materials, detailing, and construction methods.
<table>
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</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>Page 7, line 20, item 6</td>
<td>Mash</td>
<td>The comment found persuasive. Revise page 7 lines 28-21 to read: “(1) ACI 376 section 8.1.1.8 - requires that the crack widths should be calculated as characteristic and not mean calculated crack widths, as per EN 1992-1-1.”</td>
</tr>
</tbody>
</table>

**1st Ballot Results (Approved w. Comment)**

<table>
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<th>Comments</th>
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<tbody>
<tr>
<td></td>
<td>remain liquid and substantially vapor tight. More specifically: &quot;</td>
<td>Pawski, Hatfield, Brannan, Krstulovic</td>
<td>and substantially vapor tight.</td>
</tr>
<tr>
<td></td>
<td>Agree with editorial changes - Hoff, Krstulovic</td>
<td></td>
<td>During the spill condition, the concrete wall will be subjected to high forces due to mechanical loads and thermal effects that will contribute to significant wall cracking.</td>
</tr>
<tr>
<td></td>
<td>Disagree - Heptay</td>
<td></td>
<td>2013.04.13 – 376-C Minneapolis: Discussed and agree with comment.</td>
</tr>
<tr>
<td></td>
<td>Agree – Jiang, Monzarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Ballard, Malhotra, Douglas, Allen, Legatos, Widianto, Hoptay, Rostczek, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
<td></td>
<td>2014.01.08 TCP text negatives requiring discussion: - Ref. no. 32, Comment 48 – Mash, Wu &amp; Garrison negatives</td>
</tr>
</tbody>
</table>

**2nd Ballot Results**

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</tr>
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<tbody>
<tr>
<td></td>
<td>EN only calculates characteristic widths. Historically US codes have cocooned the crack width requirements into the detailing rules. These were based on the Gergely Lutz expressions which used mean widths. Replace ‘as per’ with ‘in accordance with’</td>
<td>Mash</td>
<td>Agree – Jiang, Monzarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Ballard, Malhotra, Douglas, Allen, Legatos, Widianto, Hoptay, Rostczek, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
</tr>
</tbody>
</table>

**Suggested Change**

- **2014.01.08 TCP text negatives requiring discussion:**
  - Ref. no. 32, Comment 48 – Mash, Wu & Garrison negatives

- **NEW BUSINESS for CODE - JG write the new business item on code change form Q1.**

- **Disagree - Wu**
  - Suggest that:
    - a) EN 1992-1-1 should stay, as stated in ACI 376 to delete “as characteristic and not mean”

- **Disagree - Garrison**
  - b) Committee needs to review the ability of the contractor / designer to meet the requirement of 0.008” max crack width using EN equations for the spill condition (2 cryogenic temperatures). Experience shows that this is a difficult requirement to meet. Instead, perhaps ACI 376 should specify minimum rebar size and spacing within the TCP embedment zone.
<table>
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<th>Comments</th>
<th>2nd BALLOT: RESPONSE being BALLOTED</th>
<th>Suggested Change</th>
</tr>
</thead>
</table>
| 34 | Section 2.2.1  
Page 7, Line # 31  
1) Modeling  
Suggest to change to:  
1) Modeling including modeling geometry and material thermal properties | Jiang | The comment found persuasive. Revise page 7 lines 20-21 to read:  
1) “Modeling including specific tank geometry and material thermal properties” | | 2013.04.13 – 376-C Minneapolis:  
Withdrawn pending future action by main committee.  
Jeff Garrison to prepare New Business (code change form Q1) proposal to address crack width values and method of calculation. | |
| 37 | Section 2.2.1  
Page 8, Line # 2  
4) Continue analysis until steady state final temperatures are reached  
Suggest to change to:  
4) Continue analysis until steady state final temperatures are reached and the temperature distribution is obtained | Jiang | The comment found persuasive. Revise page 7 lines 20-21 to read:  
4) “Continue analysis until steady state final temperatures are reached and the temperature distribution is obtained” | | 2014.01.08 TCP text negative requiring discussion:  
~ Ref. no. 37, Comment 48 – Garrison negative | |
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>Section 2.2.2 Page 8, Line # 8 &quot;Apply dead load, prestressing and any other steady state load, iterate to equilibrium&quot;</td>
<td>Jiang</td>
<td>Suggest to change to: &quot;Apply dead, prestressing and any other steady state load&quot;</td>
</tr>
<tr>
<td>44</td>
<td>Page 8, line 10, item 3</td>
<td>Mash</td>
<td>Determine strains in section, check for Residual Compressive Zone (RCZ), check for max comp stress etc.</td>
</tr>
<tr>
<td>47</td>
<td>Section 2.2.2 Page 8, Line # 11 5) Computer crack widths at times throughout the transient where reinforcing strains are the greatest and the material yield stress</td>
<td>Jiang</td>
<td>Suggest to change to: 6) Computer crack widths at times throughout the transient where reinforcing strains are the greatest and the stresses exceed the material yield stress</td>
</tr>
<tr>
<td>49</td>
<td>Page 8, line 18, item 7</td>
<td>Mash</td>
<td>What does this mean?</td>
</tr>
</tbody>
</table>

### 2nd Ballot Results (Approved w. Comment)

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<tbody>
<tr>
<td>41</td>
<td>Suggest to change to: &quot;Apply dead, prestressing and any other steady state load&quot;</td>
<td>Jiang</td>
<td>The comment found persuasive. Revise page 7 lines 20-21 to read: &quot;To establish initial conditions, apply dead, prestressing, normal-operating thermal, and any other steady state load, then iterate to equilibrium.&quot;</td>
</tr>
<tr>
<td>44</td>
<td>Determine strains in section, check for Residual Compressive Zone (RCZ), check for max comp stress etc.</td>
<td>Mash</td>
<td>The comment found persuasive. Change text to read: 5) &quot;Determine with the initial condition defined in step 2, compute crack widths at times throughout the transient where reinforcing strains are the greatest, and exceed the material yield stress. Furthermore, at each time step determine the adequacy of the compression zone.&quot;</td>
</tr>
<tr>
<td>47</td>
<td>Suggest to change to: 6) Computer crack widths at times throughout the transient where reinforcing strains are the greatest and the stresses exceed the material yield stress</td>
<td>Jiang</td>
<td>The comment found persuasive. Change Page 8, lines 17-18 to read: &quot;Calculation of cracking and crack widths for the RLG LNG spill condition or external fire condition shall be performed using a rational engineering analysis. Both linear or non-linear finite element (FE) analysis should be used as appropriate.&quot;</td>
</tr>
</tbody>
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### Voting Member’s VOTE & COMMENTS

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<tr>
<td>Disagree - Garrison</td>
<td>Committee needs to define analysis / design requirements. Considering the variability in the possible loading conditions, variability in material properties and variability in modeling techniques it seems that a steady state analysis would be sufficient. 2014.01.08 TCP text negative requiring discussion: ~ Ref no. 41, Comment 52 – Garrison negative</td>
</tr>
<tr>
<td>Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannam, Krstulovic</td>
<td>2014.01.08 TCP text negative requiring discussion: ~ Ref no. 44 &amp; 47, Comment 54 – Garrison negative</td>
</tr>
<tr>
<td>Disagree - Garrison</td>
<td>Committee needs to define analysis / design requirements.</td>
</tr>
<tr>
<td>Agree – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhotra, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannam, Krstulovic</td>
<td>Considering the variability in the possible loading conditions, variability in material properties and variability in modeling techniques it seems that a steady state analysis would be sufficient. 2014.01.08 TCP text negatives requiring discussion: ~ Ref no. 49, Comment 55 – Mash &amp; Ballard negatives</td>
</tr>
</tbody>
</table>
### 1st Ballot Results (Approved w. Comment)

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</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Section 2.3.1 Page 8, Lines # 21 to 23</td>
<td>Jiang</td>
<td>Suggest to change to:</td>
</tr>
<tr>
<td></td>
<td>“In this case a non-linear finite element program is used in conjunction with”</td>
<td></td>
<td>- Non-linear FE material constitutive models for concrete and steel, and</td>
</tr>
<tr>
<td></td>
<td>• Non-linear FE material constitutive models for concrete and steel, and</td>
<td></td>
<td>• Crack width calculations as per EC2</td>
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<td></td>
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</table>

**Suggested Change:**

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<tbody>
<tr>
<td>50</td>
<td>Section 2.3.1 Page 8, Lines # 21 to 23</td>
<td>Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
<td>Discuss in 2.3.1 and 2.3.2</td>
</tr>
</tbody>
</table>

### 2nd Ballot Results

<table>
<thead>
<tr>
<th>Voting Member’s VOTE &amp; COMMENTS</th>
<th>Suggested Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
<td>CSA Z2376 requires that fire and spill be considered concurrently. I believe that this needs to be addressed in this paragraph.</td>
</tr>
<tr>
<td>.Disagree - Ballard</td>
<td><strong>Rational to one uninformed Engineer could be irrational to informed Engineer. Rational requires defining.</strong></td>
</tr>
<tr>
<td>.Disagree - Mash</td>
<td><strong>Rational to one uninformed Engineer could be irrational to informed Engineer. Rational requires defining.</strong></td>
</tr>
<tr>
<td>.Agree – Jiang, Moncarz, Hoff, Rushing, Hoffman, Humayum, Howe, Wu, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic</td>
<td><strong>Performing FE analysis post-process to calculate characteristic crack width, following a method, such as Eurocode 2 EN 1992-1-1 (see section 2.5 in this TN).</strong></td>
</tr>
<tr>
<td>.Agree with minor changes - Khalifa</td>
<td>Performing FE analysis post-processing to calculate characteristic crack width, following a method, such as Eurocode 2 EN 1992-1-1 (see section 2.5 in this TN).</td>
</tr>
<tr>
<td>.Agree with minor changes - Ballard</td>
<td><strong>Performing FE analysis post-processing to calculate characteristic crack width, following a method, such as Eurocode 2 EN 1992-1-1 (see section 2.5 in this TN).</strong></td>
</tr>
<tr>
<td>.Agree with changes - Widianto</td>
<td>To be consistent with Sections 2.3.1 and 2.3.2, suggest the sentence is re-worded as follows:</td>
</tr>
<tr>
<td>.Agree with changes - Ballard</td>
<td>“Non-linear or simplified finite element (FE) analysis should be used as discussed in 2.3.1 and 2.3.2.”</td>
</tr>
</tbody>
</table>

**2nd BALLOT: RESPONSE being BALLOTED**

- Non-linear FE material constitutive models
- Implementing the non-linear material constitutive relationship for concrete and steel
- Carrying out FE analysis to obtain stress contours, and
- Performing FE analysis post process to calculate crack width as per Eurocode 2 1992-1-1

The comment found persuasive. Change text to read:

“In this case, a non-linear finite element program is used in conjunction with:

- Non-linear FE material constitutive models
- Implementing the non-linear material constitutive relationship for concrete and steel
- Carrying out FE analysis to obtain stress contours, and
- Performing FE analysis post process to calculate characteristic crack width, following a method, such as Eurocode 2 EN 1992-1-1 (see section 2.5 in this TN).”

**Agree with changes - Jiang, Moncarz, Hoff, Rushing, Hoffman, Humayum, Howe, Wu, Malhotra, Garrison, Mash, Douglas, Allen, Legatos, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Brannan, Krstulovic**

**Agree with changes - Widianto**

To be consistent with Sections 2.3.1 and 2.3.2, suggest the sentence is re-worded as follows:

“Non-linear or simplified finite element (FE) analysis should be used as discussed in 2.3.1 and 2.3.2.”

To be consistent with the last sentence in Section 2.3.1 suggest that we switch the order between the current Sections 2.3.1 and 2.3.2 (i.e., present Simplified FE analysis in Section 2.3.1 and present non-linear FE analysis in Section 2.3.2). This will also be consistent with the progression of the actual design, where Simplified FE analysis is done in the preliminary design, before non-linear FE analysis.
<table>
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</tr>
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</table>
| 53 | **Section 2.3.2** Page 9, Lines # 2 & 3  
"However, it should be noted that this is a very time consuming process and is thus usually used in the preliminary design."

Suggest to change to:  
"However, it should be noted that this is a very time consuming process and is thus usually used for focusing on more critical load cases after a preliminary screen for load cases has been performed in the preliminary design."

Jiang | The comment found persuasive. Remove the whole sentence.  
**2nd BALLOT:** RESPONSE being BALLOTED  
**2nd BALLOT:** RESPONSE being BALLOTED


| 56 | **Section 2.3.2** Page 9, Lines # 4 & 5  
"Moment-Curvature Approach: The moment curvature response is obtained using a concrete section analysis program by implementing."

Suggest to change to:

Jiang | The comment found persuasive. Change text to read:

**2.3.2 Simplified Linear FE Analysis**  
**Simplified Linear FE analysis is usually used only in the preliminary design.**

**Moment-Curvature Approach: The moment curvature properties are obtained using a concrete section analysis program by implementing:**

- non-linear stress-strain material properties, and
- a non-linear shell formulation that accounts for the cracking induced stiffens redistribution.

This moment-curvature approach could only be suitable for consideration of the steady state linear thermal gradient case and should also be used only for preliminary design.


| 63 | Page 9, line 34, item 4  
Seems out of place in terms of the flow of the document.

Mash | The comment found persuasive. Edit text as shown below:

**2.3.4 Loading**  
The RLG spill case should ...

Nodal temperature transients will typically be computed in a separate heat transfer finite element or finite difference solution.  

The thermal model used for determining nodal temperatures is also a high density model which should include concrete foundation, soil thermal boundary condition, walls, roof and outside or inside ambient temperature boundary conditions. This model should also include the base slab insulation and the thermal corner protection insulation.

Disagree - Oliver | This response does not address the basic comment that this whole paragraph doesn’t belong under “Loading”. Suggest moving it to Section 2.3.3 “Mesh Type and Size”, or inserting a new section before “Loading” called “Thermal Model”. |

2014.01.08 TCP text negative requiring discussion:

~ Ref no. 63, Comment 67 – Oliver negative not addressed |
### 1st Ballot Results (Approved w/ Comment)

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<tbody>
<tr>
<td>66 A</td>
<td>Page 10 Line 10</td>
<td>Hoptay</td>
<td>On the code side of ACI 376 ASTM A706 is not referred to as low temperature reinforcing, only in the commentary. Can it be referred to as low temperature reinforcing in the technical note? The comment found persuasive. Change text to read: &quot;The concrete wall internal temperatures from the thermal model are also typically used for selection and to determine the placement of normal (A615), cold temperature (A706) and cryogenic reinforcing complying with the requirements of ACI 376.&quot; Furthermore, in a future Code revision, revisit the use of A706 materials in ACI 376 section 4.7.2.</td>
</tr>
<tr>
<td>75</td>
<td>Page 16, last paragraph in section R8.1.1.7</td>
<td>Pawski</td>
<td>It is redundant because it repeats paragraphs 2 through 4 in section 2.1 (page 7, lines 9-21) The comment found non-persuasive. The comment found to be an editorial comment. Appendix A is a &quot;copy&quot; of what is in the Code. It is provided for reader's convenience.</td>
</tr>
<tr>
<td>76</td>
<td>Page 16, last paragraph in section R8.1.1.7</td>
<td>Thompson</td>
<td>Remove the last sentence from the Code Commentary; &quot;Due to the non-homogeneous nature of concrete, calculated crack width values measured in the field will vary from calculated values, and therefore they cannot be directly compared to calculated crack widths.&quot; Section R8.1.1.7 is text copied over from the Code and provided herein for the user's benefit. Text must remain as-is to properly reflect the Code requirement. Changes to be addressed only if/once the Code has been changed accordingly.</td>
</tr>
</tbody>
</table>

### 2nd Ballot Results

#### Voting Member's VOTE & COMMENTS

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<td>Page 10 Line 10</td>
<td>Hoptay</td>
</tr>
<tr>
<td>74</td>
<td>Appendix A Pages 15-16</td>
<td>Garrison</td>
</tr>
<tr>
<td>75</td>
<td>Page 16, last paragraph in section R8.1.1.7</td>
<td>Thompson</td>
</tr>
</tbody>
</table>

### Suggested Change

- Proposed wording incorporated into 2014.01.08 TCP text.
- **2014.01.08 TCP text negatives requiring discussion:** ~ Ref no. 74, Comment 83 – Garrison & Wu negatives

- **Proposed wording:**
  - Garrison was going to forward a copy of EN 1992-1-1:2004 to Ballard for updating the code equations in the TN.
  - Garrison is Agreed, loading and consideration of need for transient analyses needs to be reviewed.

- **Agreed:**
  - Agreement – Jiang, Moncarz, Hoff, Khalifa, Rushing, Hoffman, Humayum, Howe, Wu, Ballard, Malhota, Garrison, Mash, Douglas, Allen, Legatos, Widianto, Hoptay, Roetzer, Oliver, Pawski, Hatfield, Braman, Krstulovic

- **Agreed with comment:**
  - Ballard

- **Agreed with comment – Ballard:**
  - Garrison is Agreed with comment – Ballard.

- **Agreed with comment:**
  - Ballard

- **Agreed – Ballard:**
  - Garrison’s agreement – Ballard for updating the code equations in the TN.
### ADDITIONAL COMMENTS included with the ballots

<table>
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</table>
| Page 4, line 8; Section 1.1 | Oliver | EDITORIAL: Add “the”
“The primary function of TCP is to protect the already highly...” | Note - Added to TCP-TN markup (2014.01.08) |
| Page 6, Lines 28 - 30 | Hoff | Can we provide some guidance to the owner in this section? | 10-21: Hoff comment resolution: The crack width requirements in section 6 are provided to for this purpose. DELETE 1.2.4 |
| Page 6, Lines 28 - 30 | Wu | Why do we need additional tightness criteria on “embedding plates” to be defined by owner? | Note added to TCP-TN markup (2014.01.08) that new “1.2.4 Step 4” is to be deleted, and is shown for information. |
| Page 7, line 8 | Pawski | Referenced section does not match final 376-10 1) ACI 376 section 6.3.6.3.2” 2) ACI 376 section 6.3.6.3.3” | Note - Added to TCP-TN markup (2014.01.08) |
| Page 7, line 14 | Pawski | Referenced section does not match final 376-10 1) ACI 376 section 6.3.6.3.2” 2) ACI 376 section 6.3.6.3.3” | Note - Added to TCP-TN markup (2014.01.08) |
| Page 9, section 2.3.3, lines 19 | Khalifa | Add “separate” before model for clarity | Note - Added to TCP-TN markup (2014.01.08) |
| Page 9, section 2.3.1, line32, 33 | Khalifa | Revise to: Either a proprietary or one of several commercially available FE programs can be used for performing this calculation. | From hand notes: “Concur, combine first two sentences” Note - Added to TCP-TN markup (2014.01.08) |
| Page 9, line 24 | Hoff | Change this sentence to read: “If Liner are considered as structural members, they should be included if they are considered as structural members too.” | 10-21-13 Editorial Note - Added to TCP-TN markup (2014.01.08) |
| Page 10, line 28 | Pawski | Use “should” in a non-mandatory TN “Recognized concrete constitutive models shall should be used in the analysis.” | 10-21-13 Editorial Note - Added to TCP-TN markup (2014.01.08) |
| Page 10, section 2.4.1, line 30 | Khalifa | Revise to: “account for reduction in tensile stiffness after cracking of concrete including the effects of tension stiffening. | 10-21-13 Editorial Note - Added to TCP-TN markup (2014.01.08) |
| Page 11, line 7 | Hoff, Widianto | The stress symbols are missing | 10-21-13 Editorial Note - Added to TCP-TN markup (2014.01.08) |
| Page 12, lines 10, 11 | Hoff | Change to read: “Since for the RLG spill case, it is critical that cryogenic liquid be prevented from migrating behind the TCP, and conservative assumptions should be used when selecting material properties.” | 10-21-13 Editorial Note - Added to TCP-TN markup (2014.01.08) |
| Page 13, Section 2.5 | Wu | The specified Code, EN2 part 1 - 4.4.2.4 does not contain the equations for crack width calculation. The crack width calculation is shown in Section 7.3.4 of EN 1992-1-1 (2004 edition). Also, the equations shown here are not the same as the equations shown in EN 1992-1-1 (2004 edition). Please provide clarification. | 10-21-13 Editorial Note - Added to TCP-TN markup (2014.01.08) |
Conspicuous by its absence in the TCP-TN write-up is any reference to outer-wall designs that incorporate an impervious, continuous liquid-tight and vapor-tight liner. This omission overlooks the crucial role such a liner plays in the formulation of criteria and parameters as they pertain to (a) the serviceability of the outer wall following a spill and/or thermal shock; (b) the specified limits on crack-width, residual wall compression, etc., etc.; and (c) the function, scope and design of the TCP itself.

Moreover, this omission overlooks the differences between inner-versus-outer, and metallic-versus-non-metallic liners; and the role these differences similarly play in (a) through (c) above.

If I am not mistaken, the only Code section that fleetingly mentions this subject with respect to the TCP is Section 6.3.3. This article provides guidance on what to do if a “leak-tight membrane/liner” is not used, but does not say anything about what to do in cases where such a liner is in fact used.

The subject is also covered in 6.3.16.1 and 16.3.16.2, but those sections do not relate to the TCP.

While I have not thoroughly perused the rest of the Code itself to see exactly where else this subject “belongs” and how it should be covered, I believe that TCP-TN coverage might fit in the following sections:

- Section 1.1 (add a fifth paragraph)
- Fig. 1.1 (add Fig. 1.1 c)
- Section 1.2.4
- Section 2.1