Dr. Sanjay Mehta is Chief Technical Officer at Preload Inc., New York. He is a licensed Professional Engineer in many States in the United States and the Province of Alberta, Canada. He is also a licensed Structural Engineer in the State of Washington. His areas of interests are earthquake engineering and seismic design, finite element analysis, design and construction of wirewound prestressed concrete tanks, seismic design and evaluation of long span truss bridges and software development. He is actively involved in ACI 350-F, subcommittee and AWWA D110 committee.

**Presentation Outline**

1. Design and Construction of AWWA D110 - Type III Tanks
2. Seismic Load Path at Wall Base Joint
3. Pull Out Tests for Shotcrete-Diaphragm Interface
4. Theoretical Basis for "Development Surface"
5. Pull Test for Shotcrete-Diaphragm-Base Cable System
6. Conclusions

**AWWA D110- Type III- Tank Cross Section**

**Mechanically Seaming Steel Diaphragm**
Benefits of Pre Cast Wall Panels

- Low concrete slump & water-cement ratio possible
- Better concrete compaction
- Concrete test results available before placing panel on footing
- Steel diaphragm ensures watertightness

Waterstop Encasement

Tank Prestressing

Shotcrete Cover on Prestressed Wire

Seismic Load Path: Diaphragm-Shotcrete-Base Cables

CONCERN:

CAN PLAIN VERTICAL SURFACE OF DIAPHRAGM TRANSFER SEISMIC UPLIFT FORCE TO THE BASE CABLE THROUGH SHOTCRETE?

AWWA D110-04 TABLE 2: DIAPHRAGM-SHOTCRETE BOND STRESS = 2.5 * f'c = 158 psi (4000 psi Conc).
CONCERN….  
AWWA D110-04 TABLE 2 SPECIFIES VALUE FOR BOND STRESS  
IT IS MORE APPLICABLE IN HORIZONTAL DIRECTION WHERE DIAPHRAGM RIBS PROVIDE MECHANICAL INTERLOCK WITH SHOTCRETE  
WHAT IS APPROPRIATE VALUE OF BOND STRESS IN VERTICAL DIRECTION?  
IS THERE ANY NEED TO CHANGE DIAPHRAGM FABRICATION PROCESS TO FURTHER INCREASE THE BOND STRENGTH IN VERTICAL DIRECTION?  
NOT ENOUGH INFORMATION AVAILABLE IN THE LITERATURE- UNIQUE SITUATION FOR THIS TYPE OF STRUCTURE IN HIGH SEISMIC ZONES  
PRELOAD CONDUCTED SOME TESTS TO ANSWER THESE QUESTIONS  

BOND STRENGTH  
REINF. STEEL v/s DIAPHRAGM SHEETS  
FACTORS THAT INFLUENCE THE BOND STRENGTH OF REBAR HAVE BEEN STUDIED FOR WELL OVER 100 YEARS- ACI 408R IS THE STATE-OF-THE-ART REPORT  
REBAR IS A LINE ELEMENT  
DIAPHRAGM FABRICATED PER ASTM A 1008 IS A THIN SURFACE ELEMENT- 26 GAGE (0.017\text{in}).  
EVEN #3 BAR (0.375\text{ in}.) IS 22 TIMES THICKER THAN DIAPHRAGM  
BOND STRENGTH OF DIAPHRAGM SHEET IS NOT STUDIED AS RIGOROUSLY AS REINFORCEMENT BECAUSE SUCH A SITUATION OCCURS ONLY IN TYPE III TANKS  

TEST SPECIMENS  
TWO SPECIMENS AS SHOWN WERE FABRICATED AT A JOB SITE  

TEST SPECIMENS…  
REINFORCEMENT PLATE  
SPECIMEN WITH BOTTOM REINFORCEMENT PLATE IN POSITION  

TEST SET UP  

TEST SET UP….  

RESULTS - FAILURE MODES

TEST SPECIMENT 2 - DIAPHRAGM TENSION FAILURE

TEST SPECIMENT 1 - DIAPHRAGM SLIP / PULL OUT

RESULTS.....

<table>
<thead>
<tr>
<th>Test Load</th>
<th>Stress</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16,967Lbs</td>
<td>26.2psi Diaphragm slip/ bond failure</td>
</tr>
<tr>
<td>2</td>
<td>20,938Lbs</td>
<td>32.3psi Diaphragm tension failure</td>
</tr>
</tbody>
</table>

Bond strength is in the same range as tensile strength of diaphragm.

Increasing diaphragm bond strength by introducing deformation in vertical direction will simply change the failure mode from diaphragm slip to diaphragm fracture.

What should be the design approach for seismic load path from diaphragm to shotcrete to base cables?

SOLUTION....

Mobilize sufficient surface area of diaphragm - shotcrete interface such that failure mode is governed by yielding of base cables.

Response reduction factor (R=3.25) specified in codes is based on energy dissipation associated with ductile yielding of base cables assuming other failure modes are precluded.

EQUATION FOR DEVELOPMENT SURFACE

The tensile strength of the diaphragm:

\[ P_T = A_D W f_Y \]

\[ A_D = \text{cross section area of diaphragm per unit width} \]
\[ W = \text{width of the diaphragm}= 1'-6" \text{ in this case} \]
\[ f_Y = \text{yield strength, maximum of 40ksi per ASTM A 1008} \]

The bond strength of the diaphragm:

\[ P_B = W L \tau \]

\[ \tau = \text{ultimate bond stress per unit surface area.} \]
\[ L = \text{Diaphragm embedded in shotcrete=1'-6" in this case} \]

DEVELOPMENT SURFACE..

Equating:

\[ F_T = F_B \]

Development length:

\[ L_d = \frac{A_D f_Y}{(144 \times \tau)} \]

\[ L_d = 2.83 \beta \]

For:

\[ \tau = 26.3psi \]
\[ f_Y = 40ksi \]
\[ A_D = 0.267sqin/FT \]

Development surface = \( L_d \times W \)

DUCTILE FAILURE MODE

So long as bond stress over \( L_d \times W \) is mobilized by base cables, diaphragm pull-out or tension failure will not govern. Equating tensile strength of base cables to bond stress over surface area \( A \) \( \times \tau \) will ensure ductile failure mode.
FULL-SCALE TEST
(WITHOUT BENEFIT OF PRESTRESS AND CURVATURE)

FULL SCALE TEST SETUP

0.65*0.30=97.5T=195KIPS
BOND= 195KIPS
(2*4*4*144) BOND = 42.3psi

FAILURE MODE

RESULTS OF FULL SCALE TEST
AVAILABLE BOND STRENGTH OF 42.3PSI IN VERTICAL DIRECTION EVEN WITHOUT CONFINEMENT AND PRESTRESSING EFFECTS
ACTUAL CONSTRUCTION MORE ROBUST THAN TEST SET UP:
WALLS POUR ED VERTICALLY FOR THE TEST SET UP
NO PRESTRESS AND CONFINEMENT FOR THE TEST SET UP
NO CURVATURE OR REDISTRIBUTION EFFECTS
ALL THESE ADD TO STRENGTH/DUCTILITY OF THE SYSTEM

FAILURE MODE...

CONCLUSIONS
PULL OUT OF DIAPHRAGM IN CASE OF A SEISMIC UPLIFT CAN BE AVOIDED BY PROPER DETAILING
ANY ATTEMPT TO INCREASE BOND STRENGTH (WITHOUT INCREASING TENSILE STRENGTH) WILL NOT IMPROVE SYSTEM DUCTILITY BECAUSE THE FAILURE MODE WILL SIMPLY SHIFT FROM DIAPHRAGM PULL OUT TO DIAPHRAGM TENSION FAILURE
PROPER DETAILING TO MOBILIZE SURFACE AREA OF SHOTCRETE IS THE BEST METHOD TO ENSURE THAT FULL STRENGTH AND DUCTILITY OF BASE CABLE IS MOBILIZED