Methods to Analyze Petroleum Pipelines Subjected to a Contingency Level Earthquake

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Presentation Topics

- Summary of MOTEMS piping requirements
- Reconciling lack of performance-based acceptance criteria in ASME piping codes
- Typical input requirements for piping analysis
- Level of detail for adequate analytical modeling

MOTEMS Seismic Motions

- ***3104F.2.1 Design Earthquake Motions.*** *Two levels of design seismic performance shall be considered. These levels are defined as follows:*
- ***Level 1 Seismic Performance:***
  - *Minor or no structural damage*
  - *Temporary or no interruption in operations*
- ***Level 2 Seismic Performance:***
  - *Controlled inelastic structural behavior with repairable damage*
  - *Prevention of structural collapse*
  - *Temporary loss of operations, restorable within months*
  - *Prevention of major spill (≥ 1200 bbls)*

Earthquake Levels vs. Risk Classification

Risk Classification	Seismic Performance Level	Probability of Exceedance in 50 years	Return Period (years)	Exposed Oil (bbls)	Yearly Transfers per Year per Berthing System	Maximum Vessel Size (DWTx1000)
HIGH	Level 1	50%	72	≥ 1,200	N.A.	N.A.
	Level 2	10%	475			
MODERATE	Level 1	65%	48	< 1,200	≥ 90	≥ 30
	Level 2	15%	308			
LOW	Level 1	75%	36	< 1,200	<90	< 30
	Level 2	20%	224			

When MOTEMS Requires Analysis

- ***3109F.2 Oil Piping and Pipeline Systems.*** *All pressure piping and pipelines for oil service shall conform to the provisions of API Standard 2610, ASME B31.3 or B31.4 as appropriate, ……*
- ***3109F.3 Pipeline Stress Analysis (N/E).*** *Pipeline stress analysis shall be performed for:*
  - *New piping and pipelines*
  - *Significant re-routing/relocation of existing piping*
  - *Any replacement of "not in-kind" piping*
  - *Any significant rearrangement or replacement of "not in-kind" anchors and/or supports*
  - *Significant seismic displacements calculated from the structural assessment*
- *Piping stress analysis shall be performed in accordance with ASME B31.4 [9.3], considering all relevant loads and corresponding displacements determined from the structural analysis described in Section 3104F.*

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Analysis of Existing Pipelines

- MOTEMS only requires consideration of displacements resulting from structural assessment if there are no other changes
  - Dynamic displacements associated with structural response
  - "Static" displacements associated with liquefaction settlement, lateral spread displacement, slope failure, or compaction
- What about criteria that require both consideration of inertial and displacement?
  - Generally not appropriate for use, need to consider inertial loads even if not required by MOTEMS

Provisions for Buried Pipelines

- ***3106F.5.3 Underground Structures.*** *Buried flexible structures or buried portions of flexible structures including piles and pipelines shall be assumed to deform with estimated ground movement at depth.*
- *As the soil settles, it shall be assumed to apply shear forces to buried structures or buried portions of structures including deep foundations.*

MOTEMS Requirements vs. Referenced Piping Codes

- MOTEMS defines two levels of earthquake performance
- ASME B31 piping codes do not address ultimate performance that focus on “pressure” integrity
- Complying with ASME B31 codes for the Level 2 earthquake negates the need to consider the Level 1 earthquake
- Alternate acceptance criteria are justified in cases where typical B31 code criteria can not be met for the Level 2 earthquake
- Despite conservatism in applying B31.4 to Level 2 earthquake design, new piping systems are often capable of meeting requirements as stated without substantial difficulty

Comments on ASME Code Provisions for Piping

- ASME piping codes have an unofficial hierarchy
  - Class 1 nuclear
  - Class 2 nuclear
  - Class 3 nuclear
  - B31.1 power
  - B31.3 process
  - B31.8 gas
  - B31.4 liquid hydrocarbon
- No B31 piping codes provide a commentary
- “Essential” summary of nuclear code requirements
  - “Basis for Current Dynamic Stress Criteria for Piping,” G.C. Slagis, Welding Research Council Bulletin 367, September, 1991.

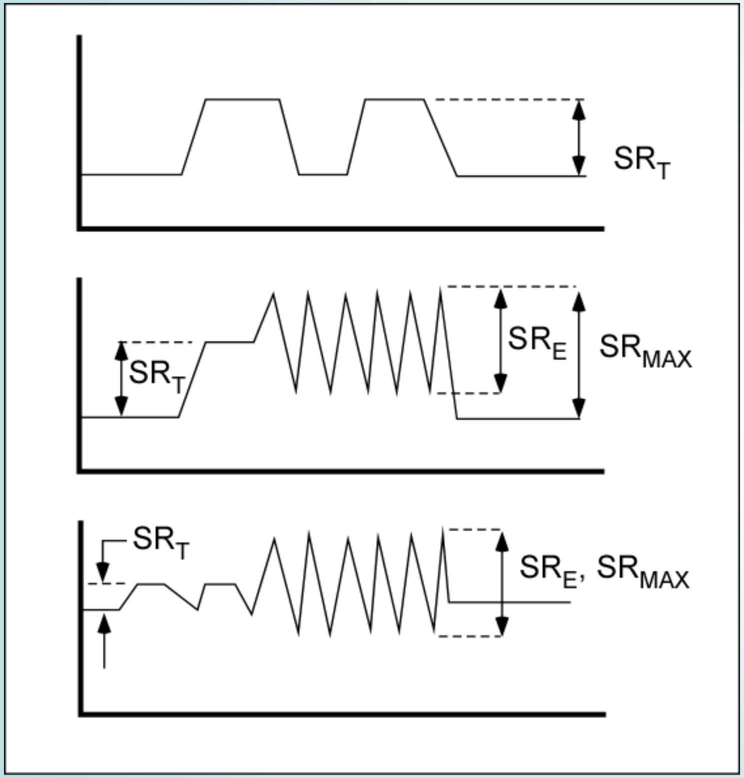
Review of ASME B31.4 Allowables

- Pressure: 0.72 x E x S_y
- Shear: 0.45S_y
- Bearing: 0.90S_y
- Expansion Stress Range:
  - Restrained: 0.9S_y
  - Unrestrained: 0.72S_y
- Sustained Longitudinal (pressure, weight, external loads):
  - Restrained: 0.9 x 0.75S_y ~ 2/3S_y
  - Unrestrained: 0.72 x 0.75S_y ~ 1/2S_y
- Occasional Longitudinal: 0.8S_y
- Offshore criteria
  - Longitudinal less than 0.8S_y
  - Combined less than 0.9S_y
  - Strains beyond yield allowed if serviceability not impaired

Restrained vs. Unrestrained

- B31.4 covers both buried and aboveground pipelines
- Buried pipelines are typically assumed to be restrained against axial elongation that can produce bending stresses at bends and elbows
  - Higher allowable for restrained pipelines likely related to assumption of development of plastic hinge (pipe shape factor is ~1.3 and 1.3(0.72) ~0.9)
  - In reality, buried pipelines under high axial loads (high temperature, imposed ground movement) will undergo displacement at buried elbows and are more unrestrained than restrained

ASME Stress Range



- For hot lines with significant thermal stress range (SR_T), the maximum stress range with earthquake uses ½ the earthquake stress range (SR_E)
- For cold lines, the full earthquake stress range is used (twice the stress nominally calculated with an equivalent static load)

ASME B31.4 Stresses

- Pressure: $S_h = PD/2t$
- Expansion:
  - Restrained: $S_L = E\alpha\Delta T - \nu S_h$
    (add S_b from weight if applicable)
  - Unrestrained: $S_E = \sqrt{S_b^2 + 4S_t^2}$

$$S_b = \frac{\sqrt{(i_i M_i)^2 + (i_o M_o)^2}}{Z}$$

Alternatives to B31.4

- B31.3 – Process Piping
  - Listed as a reference piping code in MOTEMS
  - Typically not used for the design of petroleum pipelines
- NC-3600 – Class 2 Nuclear Piping
  - Provides requirements for varying performance levels
  - Specifically addresses primary and secondary seismic stresses
- B31.E – Standard for the Seismic Design and Retrofit of Aboveground Piping Systems
  - Developed to provide more explicit guidance on how to use ASME B31 codes for seismic evaluation
  - Primarily intended to be applied with buildings and facilities designed in accordance with the IBC
  - Does not address multiple levels of performance

B31.3 – Process Piping

- Different allowable stress values
  - lesser of 1/3 S_u or 2/3 S_y at minimum S_c and maximum S_h temperature
- Pressure and Sustained Longitudinal, S_L: S_h
- Displacement Stress Range, S_A: $f(1.25S_c + 0.25S_h)$
  - f is a fatigue reduction factor (1.0 for less than 7,000 cycles)
  - S_A often greater than $0.5S_u$ or S_y (compared to $0.72S_y$ in B31.4)
- Occasional Plus Sustained Longitudinal: $1.33S_h \sim 0.9S_y$

Section III - Division 1 – Subsection NC
Class 2 Components
Rules for Construction of Nuclear Facility Components

- Only nuclear rules recognize various design service levels (Level A through D)
- For 2-level seismic hazard, lower level considered Level B (occasional) and upper level considered Level D (faulted)
- Design service levels developed in 1970 based upon judgments regarding factor of safety in design and likelihood of event occurring

Service Level	Description	Probability of Load in 40 Years	Approx. Mean Return Period (yrs)	Factor of Safety
A	Normal	1	1	3.0
B	Upset	10^{-1}	400	2.25
C	Emergency	10^{-2}	4,000	1.8
D	Faulted	10^{-3}	40,000	1.5
		10^{-4}	400,000	1.29
		10^{-5}	4,000,000	1.13
		10^{-6}	40,000,000	1.0

Level B Service Limit

$$\frac{PD}{4t} + B_2 \frac{M_{sustained} + M_{occasional}}{Z} \leq \min\left[1.8S_h,\ 1.5S_y\right]$$

- Only half of stress range used
- Can include effects of anchor displacement with occasional loads
- If anchor displacement not included above, they must be included with thermal expansion in one of the below checks

Thermal Expansion

$$\frac{iM_{thermal}}{Z} \leq S_A$$

Sustained Plus Thermal Expansion

$$\frac{PD}{4t} + 0.75i\frac{M_{sustained}}{Z} + i\frac{M_{thermal}}{Z} \leq S_h + S_A$$

- Single, non-repeated anchor displacement treated separately

$$i\frac{M_{1AM}}{Z} \leq 3S_c = \min\ S_u,\ 2S_y$$

Level D Service Limit

(for straight pipe)

$$\frac{PD}{4t} + B_2 \frac{M_{sustained} + M_{occasional}}{Z} \leq \min\left[3S_h,\ 2S_y\right]$$

- Same as Level B but higher allowable stress

$$C_2 \frac{M_{anchor} + M_{reverse}}{Z} \leq 6S_h$$ ($3S_h$ for unbalanced conditions)

$$\frac{F_{anchor} + F_{reverse}}{A} \leq S_h$$

ASME B31.E - 2008

$$\frac{PD}{4t} + 0.75i\frac{M_{sustained} + M_{seismic}}{Z} \leq \min\left[2.4S,\ 1.5S_y,\ 60ksi\right]$$

$$\frac{F_{SAM}}{A} \leq S_y$$

- Consistent with Service Level B
  - Combines seismic effects (inertia and seismic anchor motion) with other sustained longitudinal stresses
  - Limits axial stress from seismic anchor motion to less than yield
  - S is B31 stress (0.8 S_y for B31.4)

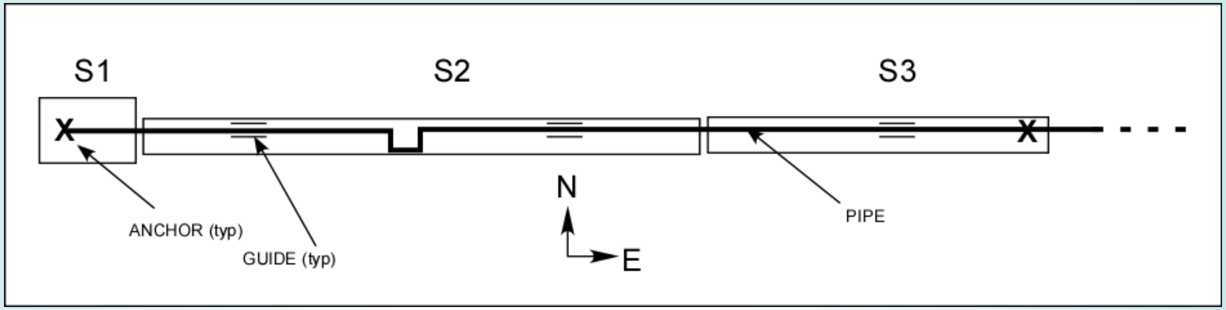
Suggestions

- ASME B31.4 is not compatible with performance-based MOTEMS criteria and is most applicable to design for the Level 1 earthquake
- The adoption of ASME B31.E provides a better approach for the Level 1 earthquake
  - B31.E is consistent with Service Level B for Class 2 nuclear piping
  - Alternate treatment of seismic anchor motion, as permitted for Service Level B is considered an appropriate deviation from the stress checks in B31.E
- Higher allowable stresses are justifiable for the Level 2 earthquake, consistent with increased allowable for Service Level D
  - Increase B31.E longitudinal and bending stress allowable to lesser of $3S_h$ or, $2S_y$
  - Increase axial stress allowable to $3S_h = S_u$

Input Requirements for Analysis

- Permanent ground displacements at pipe supports (horizontal and vertical) [N/E]
- Seismic displacements of structural elements supporting pipeline [N/E]
- Response spectrum developed considering dynamic response of structural elements [N]
  - Conservatively scaled ground motion spectrum
  - Envelope of all spectra
  - Individual spectra

Combining Multiple Structural Displacements



- Assume structures can respond in N and E directions without interference and there is no torsion
- Combinations of structural displacements need to be considered that will identify the governing case for piping stress
  - Piping stresses are from an elastic analysis (requirement for ASME code checks)
  - Stresses for all possible combinations can be determined from the results of 6 cases with a unit displacement of each structure in the N and E directions
  - Judgment and examination of piping layout can substantially reduce effort to identify most critical combinations
- SRSS (or equivalent) combinations appropriate to account for likelihood of peak N and E components acting simultaneously and peak response of the individual structures acting simultaneously
  - e.g. $(S1N^2+S2S^2+S3N^2+S1W^2+S3E^2)^{0.5}$

Analytical Refinements Usually Considered Unnecessarily Complex

- Non-linear time-history analysis to account for sliding friction or gaps in piping supports
  - Equivalent static loading based upon structural spectra and piping system frequency response is consistent with simplified static criteria in B31 codes
  - Possible exception for cases where high friction supports, dampers or other devices specified to increase effective damping
- Explicit modeling of piping support members in lieu of approximate estimate or bounding support stiffness
- Coupled piping-structure models

Summary

- Piping performance requirements in MOTEMS are not compatible with intent of B31 codes
- In the majority of cases, piping will meet B31.4 criteria for Level 2 MOTEMS seismic loading
- Options to design and assess piping that are more compatible with the intent of MOTEMS require going outside of the B31 codes
- ASME code requirements for piping are based upon static loading considerations and equivalent static approaches for assessing dynamic piping stresses are considered adequate
  - Modal analyses are often more efficient than effort to justify selection of equivalent static load

Questions?