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# A Benchmark Study of Design Codes on Offshore Pipeline Collapse for Ultra-Deepwater

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**Abstract**

The objective of this paper is to summarize current ultra-deepwater (i.e., up to 3,500 meters water depth) pipeline mechanical design methodologies as part of the limit state design.

The standard mechanical design for ultra-deepwater pipelines in the Gulf of Mexico (GOM) is based on API RP 1111. API code also has been used for deepwater projects in west Africa. DNV code OS-F101 was mostly used for deepwater projects in offshore Brazil and Europe. Some pipeline designs in the GOM have started to incorporate parts of the DNV design methodology.

A discussion of failure under collapse only and combined loading (i.e. pressure + bending) is presented. The best design criteria are obtained from physical full-scale collapse testing. The comparison of the physical test data and collapse calculations using the DNV and API codes will be presented. It was found that the conservatism still exists in the collapse prediction for ultra-deepwater pipeline using modern design codes such as DNV OS-F101 and API RP 1111.

**Keywords: offshore pipeline, collapse design, ultra-deepwater**

## 1 Introduction

Installation of offshore pipelines in water depth greater than 2000 m is on the rise and many more are planned to be installed. Because of the water depth and diameter of the pipelines, many challenges arise during the design and sometimes the conventional pipe laybarges can not be used without major upgrading or modification. In addition, the concept of the allowable plastic strains during installation and operation is much different from the allowable strains in shallow water (Choi and Jo 1999, Choi and Haun 1994). The selection of installation methods and vessel capacity for laying pipelines of particular size are critical factors for the collapse design. That means the proposed lay equipment strongly influences the methodology of pipeline collapse design.

This paper presents a collapse design methodology of ultra-deepwater pipeline in the Gulf of Mexico (GOM) and the rest of world. A study on the design codes of offshore pipeline collapse for ultra-deepwater is performed.

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Brazil and Europe. Some pipeline designs in the GOM have started to incorporate parts of the DNV design methodology.

The best design criteria are obtained from physical full-scale tests for ultra-deepwater pipelines. The following is a brief discussion of collapse only design and combined loading (i.e. pressure + bending) design. The equations for collapse only and combined load of pressure plus bending due to installation are summarized in Equations (1) to (3) for API RP 1111 and Equations (4) to (7) for DNV OS-F101.

## 1.1 Collapse due to external pressure (API)

The collapse pressure of the pipe must exceed the net external pressure everywhere along the pipeline as follows:

$$(P_o - P_i) \leq f_o \cdot P_C \tag{1}$$

where fo = Collapse factor, 0.7 for seamless or ERW pipe, 0.6 for DSAW pipe
Pc = Collapse pressure of the pipe

The following equations can be used to approximate collapse pressure:

$$\begin{aligned} P_c &= P_y \cdot P_e / \sqrt{P_y^2 + P_e^2} \\ P_y &= 2 \cdot S \cdot (t/D) \\ P_e &= 2 \cdot E \cdot \left(\frac{t}{D}\right)^3 / (1 - v^2) \end{aligned} \tag{2}$$

where E = Modulus of elasticity
Pe = Elastic collapse pressure of the pipe
Py = Yield pressure at collapse
ν = Poisson's ratio (0.3 for steel)

The collapse pressure predicted by these formulas should be compared to the hydrostatic pressure due to water depth to ensure adequate wall thickness is chosen for the range of water depths to be encountered.

## 1.2 Combined bending and external pressure (API)

Combined bending strain and external pressure load should satisfy the following:

$$\frac{\varepsilon}{\varepsilon_b} + \frac{(P_o - P_i)}{P_c} \leq g(\delta) \tag{3}$$

To avoid buckling, bending strains should be limited as follows:

$$\begin{aligned} \varepsilon &\geq f_1 \cdot \varepsilon_1 \\ \varepsilon &\geq f_2 \cdot \varepsilon_2 \end{aligned}$$

where g(δ) = (1+20δ)-1 = Collapse reduction factor
δ = (Dmax - Dmin) / (Dmax + Dmin) = Ovality

ε = Bending strain in the pipe
εb = t/2D = Buckling strain under pure bending
ε1 = Maximum installation bending strain
ε2 = Maximum in-place bending strain
f1 = Bending safety factor for installation bending plus external pressure
f2 = Bending safety factor for in-place bending plus external pressure

## 1.3 Collapse due to external pressure (DNV)

The characteristic resistance for external pressure shall be calculated as:

$$(P_c - P_{el}) \cdot (P_c^2 - P_p^2) \le P_c P_{el} P_p f_o \cdot \frac{D}{t_2} \tag{4}$$

$$P_p = 2 \cdot f_y \cdot \alpha_{fab} \cdot (t_2 / D)$$

$$P_{el} = 2 \cdot E \cdot \left(\frac{t_2}{D}\right)^3 / (1 - \nu^2) \tag{5}$$

$$f_0 = \frac{D_{\max} - D_{\min}}{D} = Qvality = 2 * API\ Qvality$$

where Pel = Elastic collapse pressure of the pipe
Pp = Plastic collapse pressure of the pipe
t2 = t-tcorr

The external pressure at any point along the pipeline shall meet the following criterion:

$$P_c \le \frac{P_c}{1.1 \cdot \gamma_m \gamma_{sc}} \tag{6}$$

## 1.4 Combined bending and external pressure (DNV)

Pipe members subjected to longitudinal compressive strain and external over pressure shall be designed to satisfy the following condition:

$$\left(\frac{\varepsilon_d \cdot \gamma_\varepsilon}{\varepsilon_c}\right)^{0.8} + \frac{P_e \cdot \gamma_{sc} \cdot \gamma_m}{P_c} \le 1, \quad D/t \le 45, \ P_i < P_e \tag{7}$$

where, εd = compressive strain

$$\varepsilon_c = 0.78 \cdot (\frac{t_2}{D} - 0.01) \cdot \alpha_\eta^{-1.5} \alpha_{gw}$$

where, αh = Maximum allowed yield to tensile ratio
αgw = Girth weld factor

## 2 Installation analysis as a part of collapse design

Pipe bending strain, which occurs mostly during the installation, is a very important factor for deepwater pipes. Reductions of bending strains can be accomplished by selecting an appropriate installation method and procedure.

As more offshore pipelines have been installed increasingly in deepwater, many specialized design and installation problems have to be solved to meet the new challenges. The concept of the allowable plastic strains during installation and operation is much different from the allowable strains in shallow water. Because of the new challenges of installation of the pipelines in deepwater, the selection of installation method and vessel capacity for laying a pipeline of particular size is critical for the collapse design of an offshore pipeline project.

The trend of early involvement of pipeline operators in installation analysis is more important in deepwater projects to remove any potential risks. During the installation analysis of many deepwater pipelines, wide ranges of bending strains, from elastic to plastic bending strains, were estimated. The ultra-deepwater pipelines must be designed such that they maintain the structural integrity during the installation and operational lifetime. Because of the water depth of 3500 m, reel-lay or J-lay installation method is recommended (McDonald and Choi 1998).

Once the pipe stress/strain due to deepwater installation is estimated, the results will be used for the combined load design described in Section 5. Iteration of the installation analysis and the combined load design is performed for the optimum design of the pipeline. Current design codes suggest the maximum bending strain of 0.2%, if any specific installation analysis is not available.

## 3 Comparison of calculation with test data

It was found that the conservatism still exists in the collapse prediction for ultra-deepwater pipelines using modern design codes such as DNV OS-F101 and API RP 1111. The Oman India Gas Pipeline (OIGP) was designed for the water depth of 3,500 m and full-scale collapse tests were conducted and presented by Stark and McKeehan (1995). Collapse tests of OIGP were performed for the straight pipe diameter of 20-inch and 26-inch pipelines with UOE (Uing, Oing, and Electric welding) process. These pipes were put into the pressure cylinder and the internal pressures corresponding to the water depths were imposed. The test results of straight pipes are as shown in Figure 1 and the combined collapse plus bending test were performed for 26-inch pipes as shown in Figure 2.

Figure 1 shows the comparison of the OIGP test data and collapse calculations using the DNV and API codes. Both DNV and API codes provide conservative results, but API shows the less conservatism. Figure 2 shows the comparison of the OIGP test data with bending plus collapse calculations. The calculated collapse pressure is very sensitive to the amount of bending strain. DNV code results in a very conservative design, whereas API code gives a less conservative design.

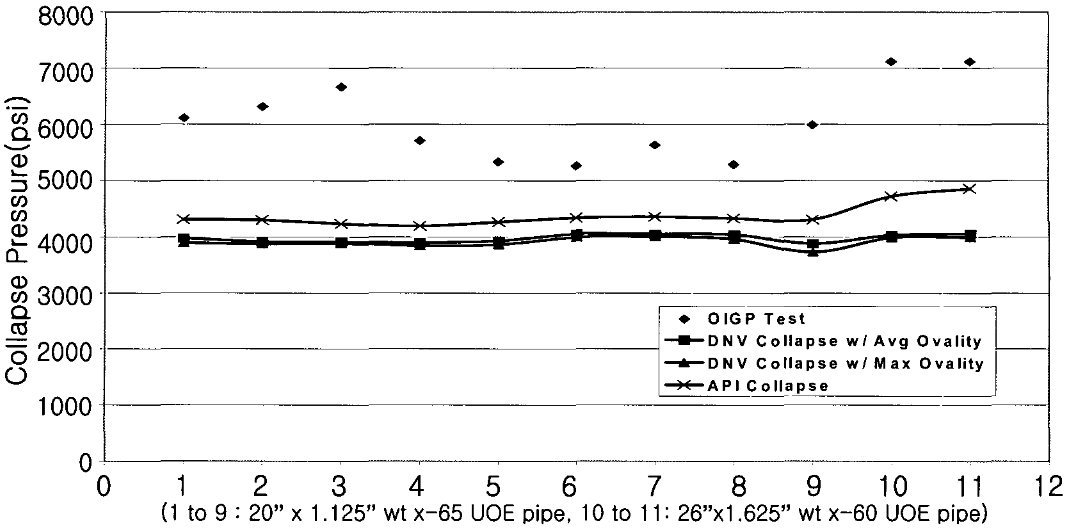


**Figure 1:** Collapse calculation and test comparison

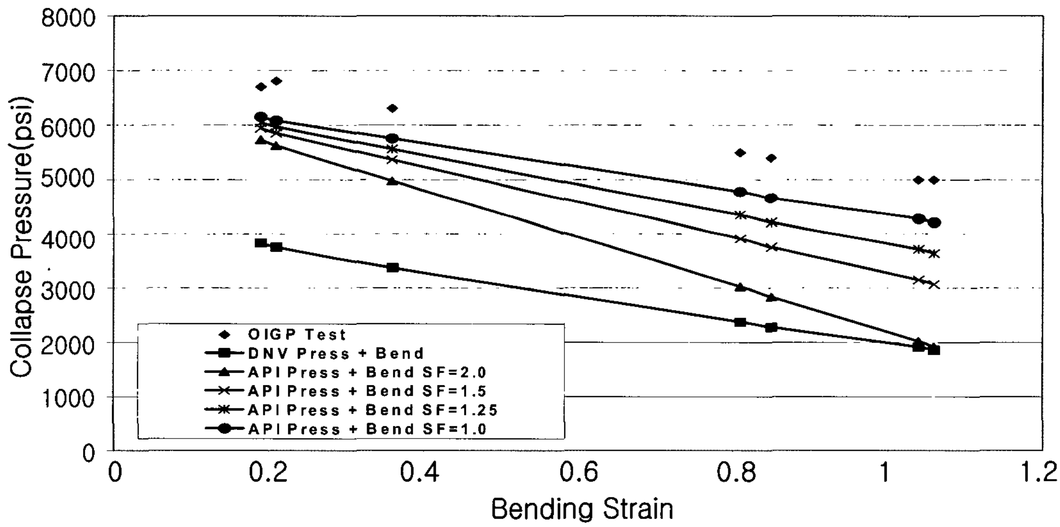


**Figure 2:** Bending + pressure calculation vs. test (26" x 1.625" WT X-60 UOE pipe)

# 4 Collapse design calculation

Figures 3 and 4 show the collapse water depths calculated from the API and DNV codes for 20-inch and 26-inch pipelines with various pipe ovalities which were caused during the construction phase in pipe mills. According to the system collapse criteria in DNV code, ovalization due to external water pressure or bending moment shall not be included. Collapse buckling water depth is strongly affected by the pipe ovality. It is important to note that the API code does not include the ovality effect for collapse. The API code is based on the ovality value specified in the API 5L line pipe code.

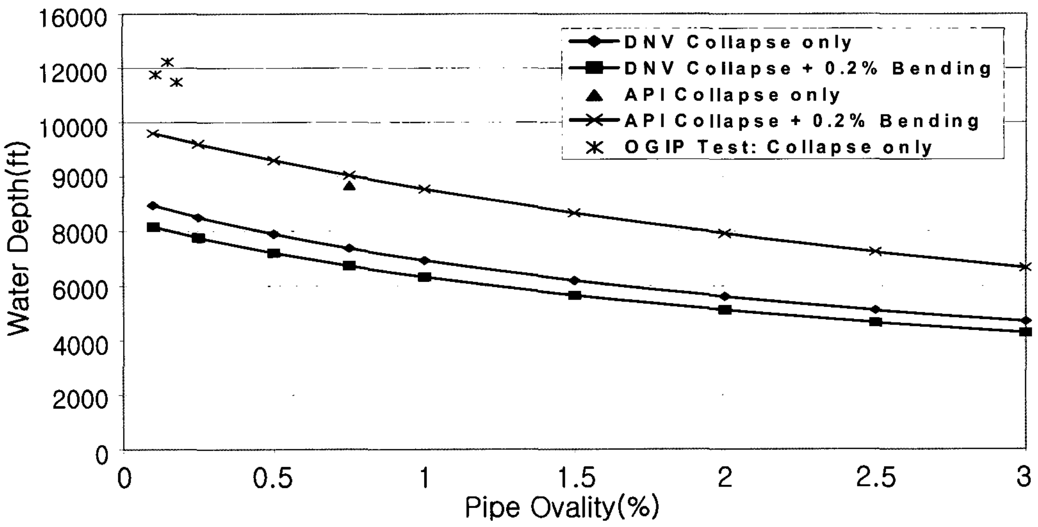


**Figure 3:** Collapse depth vs. pipe ovality (20" x 1.125" WT API 5L X-65 UOE pipe)

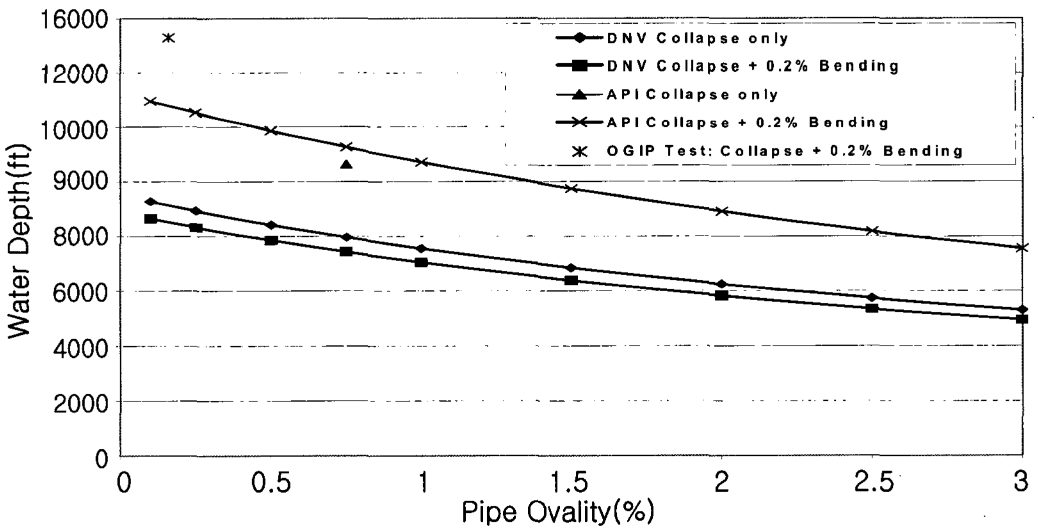


**Figure 4**: Collapse depth vs. pipe ovality (26" x 1.650" WT API 5L X-60 UOE pipe)

Figures 5 and 6 show the collapse water depths for 20-inch and 26-inch pipelines with various wall thicknesses. Both DNV and API codes provide very conservative results for ultra-deepwater. DNV code results in a more conservative design of wall thickness. The following table is a summary of some main differences in the collapse design calculations produced by the API and DNV codes.

**Table 1:** Collapse design comparison

| | API RP 1111 | DNV OS-F101 |
|---|---|---|
| Equation number | (1) | (4) |
| Comparison w/ Test (OIGP) | Conservative | Very Conservative |
| Ovality factor utilized in calculation | No<br>implied from API 5L | Yes |
| Recommendation for ultra-deepwater | No | No |

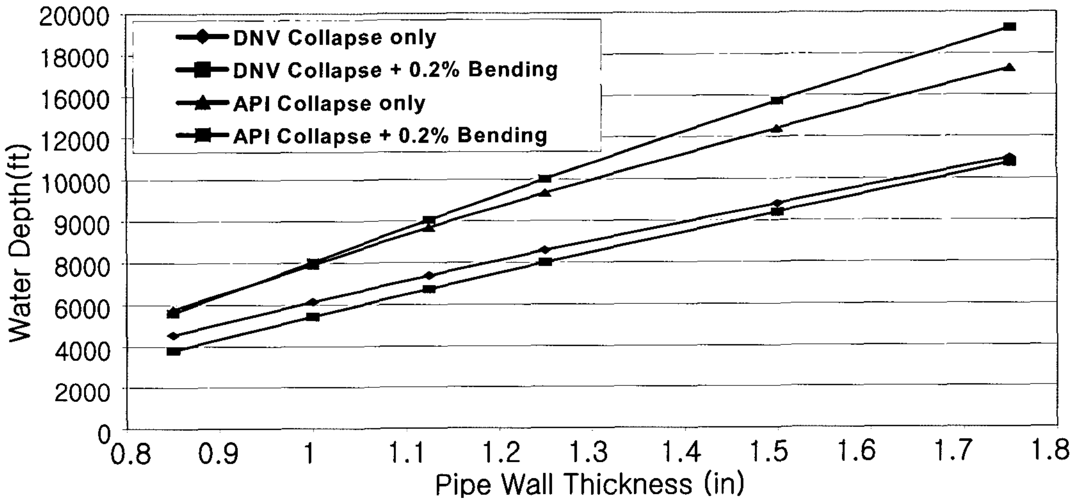


**Figure 5:** Collapse depth vs. wall thickness (20" OD API 5L X-65 UOE, ovality = 0.75%)

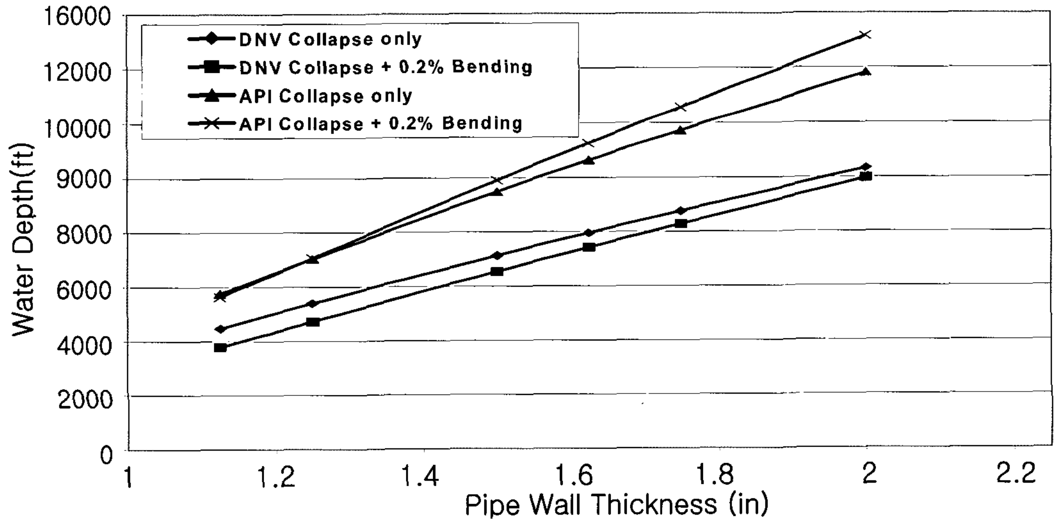


**Figure 6:** Collapse depth vs. wall thickness (26" OD API 5L X-60 UOE, ovality = 0.75%)

## 5 Combined load (bending + pressure) design calculation

Bending load and pressure are considered for combined load design calculation. Bending load is mainly from the installation and pressure is either external or internal.

Figures 3 and 4 also show the collapse water depths calculated from the API and DNV codes for 20-inch and 26-inch pipelines with combined load of bending and pressure. Figures 5 and 6 also show the collapse water depths with combined load of bending and pressure for various wall thicknesses.

Both of the criteria in the DNV code are too conservative: the calculated results are far less than the test data of collapse water depths (refer to Figures 1 through 4). DNV code will yield too thick wall thickness of pipe (refer to Figures 5 and 6). Based on these results, DNV code is not recommended especially for the deepwater pipelines.

API code results in a less conservative design than DNV code. However, the collapse resistance obtained from the combined load of bending and pressure is higher than that of obtained from the collapse only for water depth greater than 2400 m (8000 ft). It means that the collapse only criteria results in a thicker wall than the combined load criteria. These unreliable results occur only for water depth greater than 2400 m based on the collapse only criteria. The results are shown in Figures 5 and 6. Even though the collapse only criteria are not reliable, the method using API combined load design criteria (i.e., bending + pressure) for determining pipeline wall thickness is recommended for ultra-deepwater, since the load is still below the test data (refer to Figures 3 and 4).

Figure 2 shows the sensitivities of bending safety factors up to bending strain of 1.1%. Bending safety factors of combined load formula in API RP 1111 are also very sensitive to the collapse pressure. Bending safety factor 1.25 or less should be used in case of an excessive bending strain (e.g. 0.4%). The recommended bending strain during the installation should be less than 0.2%. The following table is a summary of some main differences in the collapse plus bending design calculations presented in the API and DNV codes.

**Table 2:** Combined load design comparison

| | API RP 1111 | DNV OS-F101 |
|---|---|---|
| Equation number | (3) | (7) |
| Comparison w/ Test (OIGP) | Less conservative | Very conservative |
| Ovality factor utilized in calculation | Yes | Yes |
| Recommended bending strain | 0.2% | 0.2% |
| Recommendation for ultra-deepwater | Yes | No |

# 6 Conclusions

Both of DNV OS-F101 and API RP 1111 codes have been used widely to determine the wall thicknesses of offshore pipelines up to water depth of 2000 m. However, there are not enough offshore pipeline data beyond the water of 2000 m. It was found that the conservatism still exists in the pipeline collapse prediction using these modern design codes for water depth greater than 2000 m. Following conclusions are obtained for ultra-deepwater pipelines from this benchmark study:

1. The wall thicknesses of deepwater pipelines are strongly dependent on the pipe ovalities.
2. Collapse design is very sensitive to the bending strains which can be estimated from the installation procedure.
3. DNV code is too conservative and not recommended for ultra-deepwater pipelines.
4. API code results in a less conservative design than DNV code. However, the collapse only criteria in the API code are not reliable for ultra-deepwater pipelines. Collapse only in API is not recommended.
5. Full-scale tests are recommended for ultra-deepwater pipelines.
6. If data from full-scale tests are not available, the combined load of bending and pressure in API code is recommended for wall thickness design in ultra-deepwater pipelines.

## Acknowledgements

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