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Effects of material quality and span length on the optimum design of non-standard sized above-ground pipelines

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Abstract

The optimum design is widely used in engineering practice. It is always important to aim at the best price or just material saving. The optimum dimensions of the pipeline can be determined using different steel grades, span lengths and different geometrical and loading conditions. Span length, material quality, tube diameter and thickness are variables. In this study only the material cost is minimised with non-standard sized geometrics.

Keywords:optimization, pipeline, non-standard, stress, stability, slenderness

1. Introduction

Using optimum design is the best way to find the best price or material savings. Structural optimization is one of the most developing design method in structural design. The main requirements for high load-bearing structures are safety, capacity, efficiency and manufacturability. Design and fabrication conditions are formulated at the level of analysis, as well as the objective function (Farkas and Jármai, 1997).

Theoretical and experimental knowledge of different loaded structures allows finding the optimal solution for a given task. To make sure you get the optimum solution you need a sufficient number of data. Earlier studies already carried out a number of structural optimal design, which confirmed the importance of the optimization of structures (Farkas et al., 2004, Virág, 2006 and Virág, 2009). The results are significantly influenced by the considered conditions. In this paper above-ground pipelines are investigated which look similar to the structure in Figure 1, where a pipe-bridge is not installed.

Fig. 1. An above-ground pipeline

Transportation pipelines are investigated where we disregard geometries used in practice which put a serious obstacle to finding effective structural optimum (Virág, 2013). The numerical example examined the effect of the material quality and the spanlength that these changes will influence the optimal geometry. In each calculation only the tube diameter and thickness are variables. The inner pressure is calculated for each inner diameter.

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2. Design constraints

The following conditions should be taken into account in case of design of high-pressure pipelines: stress, deflection and stability constraints, and although hydrodynamic investigation is not taken into account the velocity of flow is limited.

2.1. The limit of flow velocity

The specific conveyed medium always determines the economic flow rate (Table 1.). In case of too high flow velocity undesired phenomena may occurs e.g. noise, vibration or erosion. Therefore there is a limitation of flow velocity. In the numerical example it is limited by 20 m/s.

Table 1. Economic flow rates of gases and fluids (Juhász 1995)

Medium	Type of pipeline	Velocity (m/s)
Water	Waterworks and distribution system conduits	
	- main	1...2
	- long-distance	<3
	- local network	0,6...0,7
	Feedwater	1,5...3
	Cooling water	0,6...2
Steam	low pressure (up to 10 bar)	15...20
	medium pressure (10...40 bar)	20...40
	high pressure (60...125 bar)	40...70
Air	compressed air	20...25
Oil	Long-distance pipelines	1,5...2
	Lube oil	0,5...1

2.2. Stress constraint

The stress constraint can be calculated as known inner pressure, dead-load.
The distributed load is

$$p = \left(1,2A\rho_a + 1,1A_t\rho_g\right)g \tag{1}$$

where ρ_a is the density of the steel, A_t is the area of transportation, ρ_g is the density of high pressure gas and the area of the pipe wall is

$$A = \frac{\left(D^2 - d^2\right)\pi}{4} \tag{2}$$

In structural analysis, Clapeyron`s theorem of three moments is a relationship between the bending moments at three consecutive supports of a horizontal beam. Let *A*, *B*, and *C* be the three consecutive points of support, and denote by *l* the length of *AB* and by *l`* the length of *BC*. Then the bending moments M_A, M_B, M_C at the three points are related by

$$M_A l + 2M_B(l + l') + M_C l = \frac{6a_1x_1}{l} + \frac{6a_2x_2}{l'} \tag{3}$$

where a_1 is the area on the bending moment diagram due to vertical loads on AB, a_2 is the area due to loads on BC, x_1 is the distance from A to the center of gravity for the bending moment diagram for AB, x_2 is the distance from C to the center of gravity for the bending moment diagram for BC.
So the bending moment at the middle support according to the Clapeyron formula is

$$M_2 = \frac{2,5pL^2}{4} \tag{4}$$

where *L* is the distance between the supporters.
The stress is

$$\sigma_1 = \frac{M_2}{K_x} \tag{5}$$

where

$$K_x = \frac{\left(D^4 - d^4\right)\pi}{32D} \tag{6}$$

where *D* is the outside diameter and *d* is the inside diameter.
Barlow's formula can be calculated as

$$\sigma_2 = \frac{p_b d}{2t} \tag{7}$$

where D is the outside diameter and d is the inside diameter.
Reduced stress is

$$\sigma_R = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \tag{8}$$

The permissible stress is

$$R_{adm} = \frac{f_y}{n_e} \tag{9}$$

where safety factor n_e is 1,2 and f_y is the yield stress.
The stress constraint is

$$\sigma_R \le R_{adm} \tag{10}$$

2.3. Deflection constraint

The deflection of the pipe between the supports can be calculated as follows

$$w = \frac{pL^4}{284EI_x} \tag{11}$$

where E is the elastic modulus and the moment of inertia is

$$I_x = \frac{\left(D^4 - d^4\right)\pi}{64} \tag{12}$$

The limitation of the deflection is

$$w \le \frac{L}{300} \tag{13}$$

2.4. Stability constraint
Stability is a major problem in the construction design, because instability causes malfunction or failure in many cases. This constraint depends on the ratio between the outer diameter and the wall thickness. The limit is given by Eurocode to avoid local buckling in the tube walls:

$$\frac{D}{t} \le 90\varepsilon^2 \tag{14}$$

where

$$\varepsilon = \sqrt{\frac{235\text{MPa}}{f_y}} \tag{15}$$

3. Numerical example

The aim of this survey is to find the lowest mass per unit length pipe for a given transporting volume flow rate. To obtain this optimum, the best outside diameter and wall thickness combination has to be found. In this numerical example the mass flow rate is about 30 m^3/s of carbon dioxide. The distance between the supports are L = 20, 30, 40 and 50 m and the yield stresses of the material of the tube are f_y = 235, 355, 460, 590 and 690 MPa.

The optimum results for different tasks are calculated by Excel Solver Non-linear module which uses gradient method where the unknowns were the outside diameter and wall thickness. The results for different spanlengths and material qualities are shown in Table 2, 3, 4 and 5.

Table 2. Results for spanlength of L = 20 m

yield stress [MPa]	Outside diameter [mm]	Wall thickness [mm]	Mass per unit lenght [kg/m]
235	***1155***	***13***	***366***
355	1169	20	567
460	1181	26	741
590	1197	34	975
690	1209	40	1153

Table 3 Results for spanlength of L = 30 m

yield stress [MPa]	Outside diameter [mm]	Wall thickness [mm]	Mass per unit lenght [kg/m]
235	***1155***	***13***	***366***
355	1169	20	567
460	1181	26	741
590	1197	34	975
690	1209	40	1153

Table 4. Results for spanlength of L = 40 m

yield stress [MPa]	Outside diameter [mm]	Wall thickness [mm]	Mass per unit lenght [kg/m]
235	1921	22	1030
355	***1291***	***22***	***688***
460	1181	26	741
590	1197	34	975
690	1209	40	1153

Table 5. Results for spanlength of L = 50 m

yield stress [MPa]	Outside diameter [mm]	Wall thickness [mm]	Mass per unit lenght [kg/m]
235	3000	34	2487
355	2017	34	1663
460	1575	35	1329
590	***1243***	***35***	***1043***
690	1209	40	1153

In the tables there are optimum geometrics for different spanlengths and material qualities. The difference between these optimums can be more than double. The optimum geometrics for different spanlengths are marked by bolt italics. The smaller spanlength gives the global optimum for this case, but the costs of supports are not taken into account.

4. Conclusions

The aim of this paper was to find the lowest mass per unit length pipe for a given transporting volume flow rate. The optimum geometry is fundamentally influenced by the maximum flow velocity. Increasing the yield strength the stability constraint changes the optimum geometry. Increasing the spanlength the stress constraint than the deflection constraint becomes activated. These changing trends confirm the real value of the optimum design.

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