Types of Steel Liners

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Contributor: Araceli Martín Candilejo

There are significant levels of concern about both the safety assessment and financial evaluation of the whole hydropower system, especially at early project stages. In addition, there is a variety of reliable and accurate methods for analysis, design, and optimization of steel pressure liners in hydropower plants. Several countries have developed specific regulations and codes for the design, installation, and safety evaluation of under-pressure piping, as well as estimates of the potential risks associated with failure. This article reviews the current methodologies and codes available for design and safety assessment of either unstiffened or stiffened pressure steel liners in hydropower plants.

steel liner | penstock design | buckling failure | liner instability | pressure pipelines

1. Introduction

Over the past decades, large hydroelectric power stations have been built worldwide, with many others currently at the project or construction stage. According to estimates, power installed at pumped-storage hydroelectric power stations is expected to increase significantly during the present decade. Such plants are often designed for high flow rates and heads, which entail large-diameter and high-pressure penstocks. The increasing development of new and large-scale hydropower projects has involved a renewed research effort over the past decade with specific attention being paid to pressure steel liners [1].

The suitability of steel liner design methods is a highly relevant issue for either the technical development of new hydroelectric projects or the safety assessment of existing hydroelectric power plants in operation for more than 50 years. The accuracy of formulations traditionally used for steel-liner design, both with and without stiffeners, under external pressure is questionable. In addition, these may yield either conservative or non-conservative results depending on their ranges of application. This has led to the development of more refined, reliable, and safer design and analysis methods during the past few years. Traditional design approaches previously only considered the existing gap between the steel liner and the encasing concrete and piping out-of-roundness as the most relevant geometric imperfections. However, little focus had been given to those imperfections caused either by welding or by wall-thickness loss in corroded areas.

The aims of this paper are to gather and compare the available methods for the design and the safety assessment of steel pressure liners in current hydropower plants.

All the information can be found in the paper: "A Comparative Review of the Current Methods of Analysis and Design of Stiffened and Unstiffened Steel Liners" [2] [3].

2. Layout and Components of a Pressure Tunnel

Figure 1 depicts the typical layout of a pressure tunnel and its components:

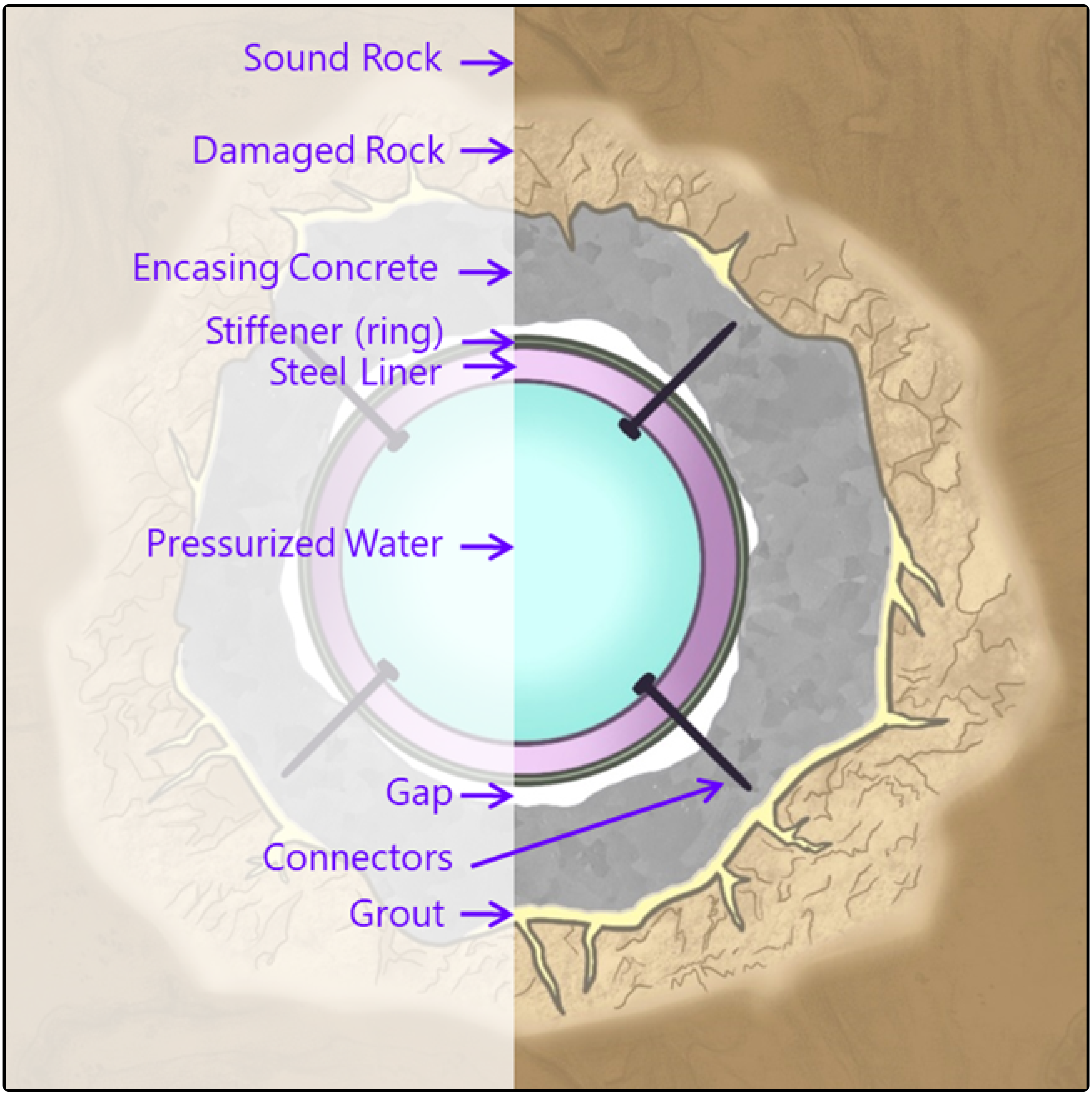
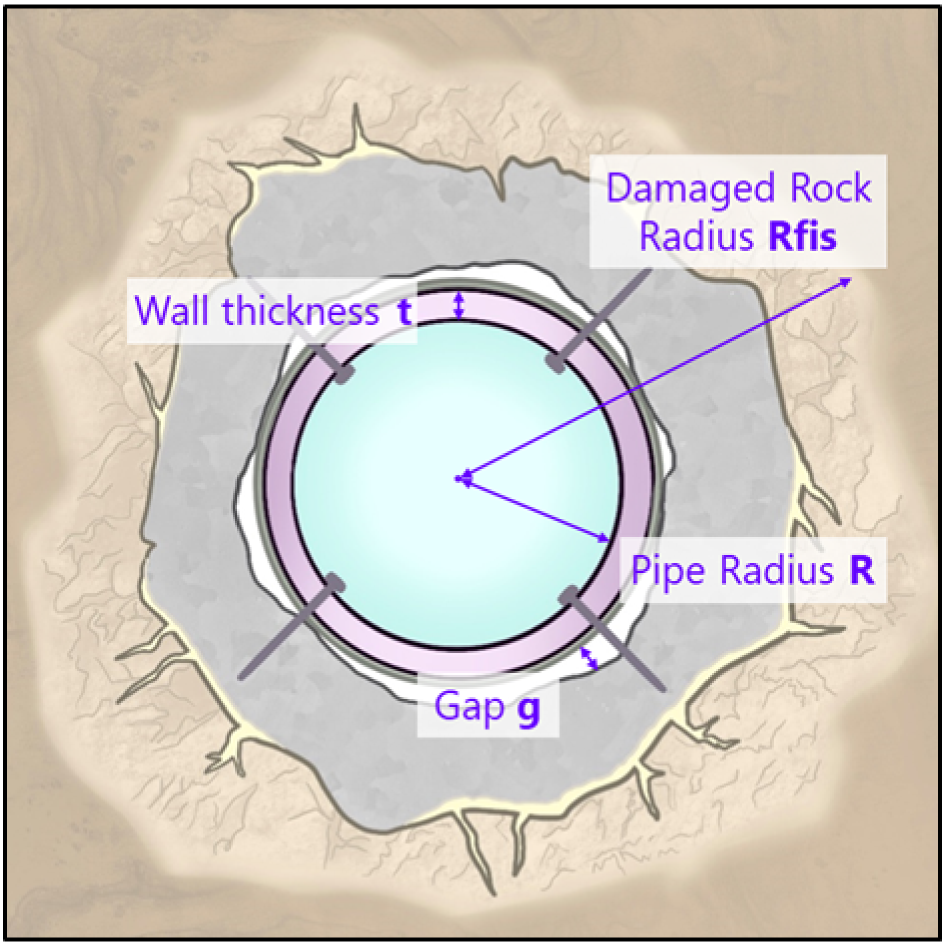


Figure 1. Layout of a pressure tunnel with a steel liner and all components.

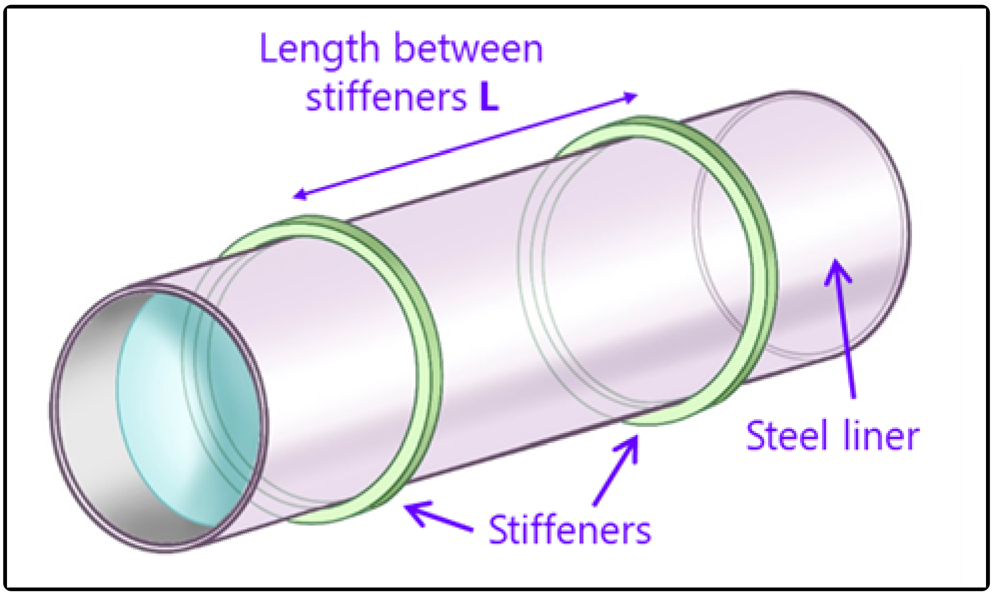
- Steel pressure liner that conveys water under pressure.
- Reinforced or mass-concrete backfill that encases the steel liner.

- An existing gap between the steel liner and the surrounding concrete.
- Grouted rock (if any) for either waterproofing or improvement of the terrain.
- Damaged rock that remains in place after blasting or excavation. The values of the outer radius of such zone may range between one and five times that of the piping. An estimate of the thickness of fissured rock may be from 0.3 to 1 m with the use of a tunnel borer and 1–2 m with blasting [4].
- Sound rock, usually assumed to be uniform, isotropic and elastic with a deformation modulus *Er*.
- Stiffeners that are attached to increase the moment of inertia of the pipe wall.
- Steel connectors anchored in concrete.

The main variables involved in the design of a steel liner have been compiled in **Table 1** and are indicated in **Figure 2**, and the main parameters are the following: D/t (the ratio between the diameter and wall-thickness of the pipeline), L/D or L/t (spacing between stiffeners), *I* (the moment of inertia of the stiffeners), the quality of the steel, g/R (ratio between the initial gap and the pipe radius), and *Ec*/*Es* (between the moduli of elasticity of the concrete backfill and the steel liner). The usual values of the geometrical parameters are shown in **Table 2**. The influence of the different parameters was studied in depth by Wang et al. [5]. During this past decade, many authors have focused on analysing in depth these variables for their particular cases [6].



(a)



(b)

Figure 2. Main variables in a liner (**a**) section and (**b**) longitudinal pipe.

Table 1. Main variables involved in the design of a steel liner.

Main variables		
R	Liner Radius[1]	Average value between the external and internal radius
D	Diameter	**D** = 2·**R**
t	Wall thickness of the liner	
I	Moment of inertia of the stiffeners	
g	Gap	
L	Span length between stiffeners	
Rfis	Radius of the fissured rock	
Ec	Moduli of elasticity of the concrete backfill	
Es	Moduli of elasticity of the steel	
E’	Moduli of elasticity of the steel under plane strain assumption	
fsy	Yield stress of the steel	
Ps	Internal pressure absorbed by the steel liner	
Pcr	Critical Buckling Pressure	
ν	Poisson's ratio	

n	Number of lobes formed in a stiffened liner. It also indicates the buckling failure mode

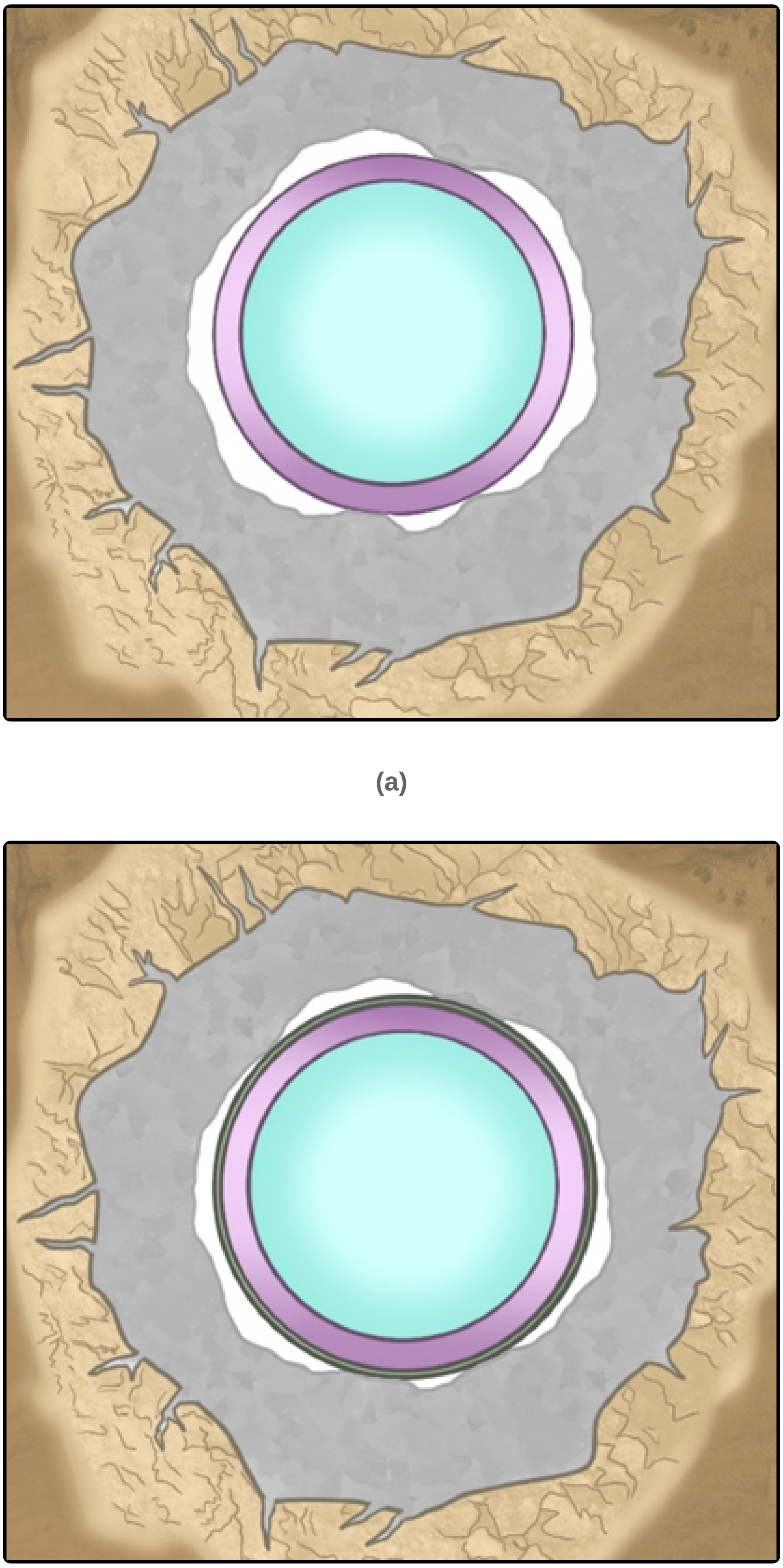
[1] Also expressed as Rs by many authors.

Table 2. Usual values of the geometrical parameters of a steel liner.

Parameter	**Range**
D/t	100 – 400
L/t	60 – 240
g/R	0.0003– 0.001

3. Types of Steel Liners

The project of a pressure tunnel involves a choice between an unstiffened liner with sufficient thickness and one thinner but with ring-stiffeners. Besides, using higher-strength steel is an additional option. The final design should draw on financial considerations and construction ease. Both types are depicted in **Figure 3**.



(a)

(b)

Figure 3. Layout of the cross-section of (**a**) Unstiffened liner, i.e., constant cross-section shaft and (**b**) Liner with a stiffening ring to increase locally further buckling resistance.

3.1. Unstiffened Liners

The liner consists of a steel cylindrical shell. It is often used when the external pressure is low and the minimum thickness imposed by transportation and installation is sufficient. It has the following advantages [7] :

- Design and calculation methods are developed with significant depth [8] [9].
- Its outer diameter is smaller than that of a steel casing with stiffeners, by which the tunnel excavation diameter will be smaller.
- Implementation is simpler, especially for wall thicknesses less than 30 mm. For greater values, welds may be more complex and entail a higher financial cost.

Use of stiffeners for wall thicknesses t greater than 38 mm is considered to be financially prudent. Up to such a thickness, the lining may be installed by using internal full-penetration welding, without any need to apply later thermal treatments to the weld (with medium- and low-strength steels).

3.2. Stiffened Liners

The stiffeners, which are equally-spaced installed along the pipe, are welded to its outer circumferential perimeter. They have the following advantages:

- They provide the steel cylinder with greater rigidity and, depending on their shape, may bind the sheet steel to the concrete (thus behaving as connectors).
- Due to their greater moment of inertia, they are lighter than a liner with the same resistance capacity.

Figure 4 shows instability modes of liners with various degrees of spacing. The formation of a larger number of lobes (*n*) for closer spacing between the stiffeners may be noted.

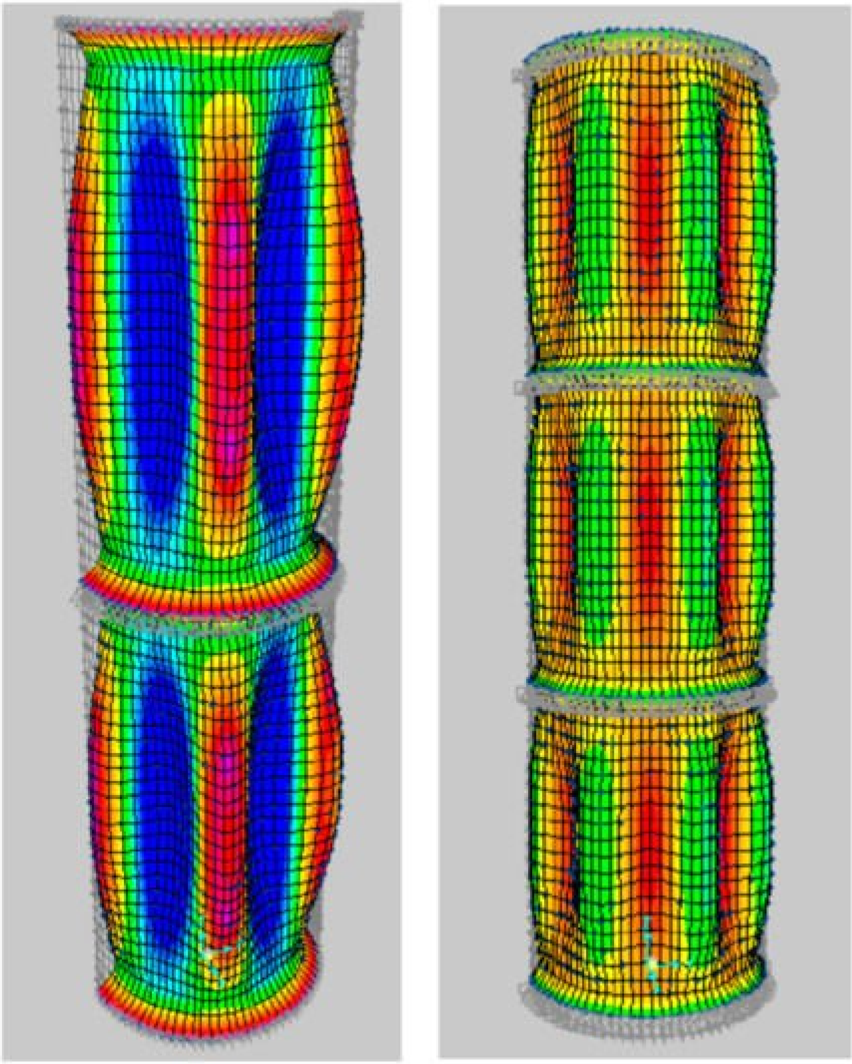


Figure 4. Geometrical instability of liners with various degrees of spacing between the stiffeners.

4. Regulations and Codes regarding Steel Liners Design

The most known codes are:

- The CECT issued a regulation[8] that explicitly makes reference to calculation of steel liners. It includes equations and nomograms derived from the Amstutz formulation and requires a safety factor greater than 1.6.
- The USACE Code [10] recommends the methods provided by Amstutz, Jacobsen and Vaughan with regard to overall instability. For analysis of local buckling of the span between stiffeners it recommends the formulations of von Mises and Donnell. Indeed, design is considered to be acceptable when the calculated stresses do not exceed 80% of the yield stress.

Other related codes are the following:

- The Boiler and Pressure Vessel Code (2001), provided by the American Society of Mechanical Engineers (ASME).

- The Technical Guide on Pipelines for the Transport of Pressurised Water, provided by the Centre for Studies and Experimentation in Public Works: (Centro de Estudios y Experimentación de Obras Públicas, CEDEX, Spain), that gathers an extensive range of Standards associated with calculation methods in pressurised water tunnels (based on the American Water Works Association Manual M11).
- ASTM F1216 (1998), published by the American Society for Testing and Materials (ASTM). [11]
- The Recommended Practice DNV-RP-C202 for the Buckling Strength of Shells, published by Det Norske Veritas. [12]
- Buckling of Steel Shells: European Recommendations, provided by the European Convention for Constructional Steelwork (ECCS).[13]
- Design Guidelines for Pressure Tunnels and Shafts AP-5273, provided by the Electric Power Research Institute (EPRI). [4]

However, design guidelines for the application of high-strength steel for steel liners are still missing [14]. For that Pachaud et al. [15] [16][17] have proposed methodology for safety assessment of the steel liners of pressure tunnels and shafts, specially motivated for the weakness that welding imperfections may affect the liners.

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