

A PROPOSAL TO HARMONIZE SAFETY CONCEPTS FOR THE DESIGN OF STEEL PENSTOCKS

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Abstract: The following contribution attempts to bring together the commonly used penstock design safety concepts from CECT and ASCE manual No. 79 by considering the different penstock support conditions, the detailed stress differentiation, and the material properties, particularly the ratio of yield to tensile strength. Since various penstock components are calculated both analytically and numerically, this proposal also provides a robust and harmonized safety concept for the application of different stress assessment techniques.

1 Overview of major penstock design guidelines

Steel penstocks are major parts of the water conveyance system of hydroelectric power plants. Above all, they must withstand the load caused by the internal water pressure. The water is conveyed in steel pipes welded together via the shortest and most economically efficient route possible and it is divided up just before the powerhouse, depending on the number of machines. Regarding the design, a distinction is made between straight cylindrical pipe sections and more complex structures like elbows and distributors. The calculation of steel plate thicknesses as a function of permissible stress is also different for these individual components. Analytical formulae are commonly used for less complex cylindrical straight pipes, whereas for special components, finite element analysis is today's state-of-the-art approach. That is exactly where the difficulty lies: Stresses that are determined by using analytical formulae are based on the nominal stress concept, whereas a finite element model does not only show nominal stresses but also locally increased stresses and even peak-stresses. All these calculated and evaluated stresses must be compared with permissible stresses, which are usually provided by guidelines and well-known standards and to which client specifications often refer, which is demonstrated on a penstock case study example in [1].

The most common European standard for the design, manufacture, and erection of steel penstocks for hydroelectric installations is still CECT [2]. If a project is executed in English-speaking countries, ASME Boiler and Pressure Vessel Code [3] and ASCE manual No. 79 "Steel Penstocks" [4], which shares the same safety concept philosophy as the ASME BPVC, are often preferred.

It should also be mentioned, that strictly speaking, CECT is today replaced by the rather unknown CODETI Version 3 [5], which is also more or less based on ASME safety philosophy.

Both well-known guidelines that specifically address steel penstock design – CECT and ASCE manual No. 79 - offer advantages: CECT allows for a clear differentiation with respect to the penstock type. The more securely the penstock is embedded in its environment, the higher its utilization is permitted. This kind of risk assessment is not taken into account in the ASCE manual, which is historically more or less based on the

ASME code for “pressure vessels”, hence stand-alone parts. However, different stress categories – as they particularly become visible when evaluating finite element models – are considered herein.

2 Introduction to CECT

The CECT safety concept is based on “global” safety factors, so-called dimensioning factors C’ (and C’’ to be applied to load cases caused by external pressures, which are not the subject of the present paper). The material yield strength Re (guaranteed elastic limit) divided by C’ results in the permissible stress σ . CECT also makes a distinction between the “type of work” (exposed or free in tunnel, buried, buried and concreted, in a concreted tunnel with and without rock collaboration), the “type of structure” (cylindrical pipes, distributors or special parts) and the “type of loading” with respect to the penstock condition (permanent, intermittent and exceptional forces caused by different load cases and load situations, see Table 1) and adapts its factors C’ accordingly.

$$\sigma = \frac{Re}{C'}$$

The stress analysis is done by comparing the calculated equivalent stress (for instance Hencky-von Mises’s criterion) based on primary stresses with the permissible stress. If primary and secondary stresses occur together, the equivalent stress shall generally be lower than the yield strength. Additional factors for this scenario are not provided, leaving the decision up to the evaluation engineer’s experience on how to quantitatively interpret “below elastic limit”.

Table 1: Dimensioning factors C’ from CECT
Indicative table of minimum dimensioning factors C

Loading case: (as para. 2 of Annexure II)	Permanent forces		Intermittent forces		Exceptional or accidental forces						
	1	2	3	4	5	6	7	8	9	10	11
Factors C’ : $\sigma_{perm.} = Re/C'$	Cylindrical pipes	Distributors or special parts	Filling or emptying	External overpressure	Pressure Test after erection	Concreting	Grouting	Waterhammer effect due to a sudden cut-	Penstock subjected to absolute vacuum	Seismic	Shop tests Transports
Factors C’’ : $P_{critical} = C'' * p_{max.}$											
				(a)		(b)	(b)		(a)		
Penstock condition	full	full	half-full section	$P_{int} < P_{ext}$	full			full	Total vacuum	full	full
Types of factors	\	\	\	\	\	\	\	\	\	\	\
Types of work											
a: Exposed or free in tunnel	1.7	2	1.5	-	1.3	-	-	1.2	1.6	1.2	1.2
b : Buried	1.7	2	1.5	-	1.3	-	-	1.2	1.6	1.2	1.2
c : Buried and concreted	1.5	1.8	1.3	1.6	1.3	1.5	2	1.2	-	1.2	1.2
d : In concreted tunnel without collaboration of the rock	1.5	1.8	1.3	1.6	1.3	1.5	2	1	-	1	1.2
In concreted tunnel with collaboration of the rock	e : steel lining only considered	1.1	1.5	1	1.6	1	1.5	2	-	-	-
	f : plate + concrete + rock assembly	2	2.5	-	1.6	1.8	-	2	-	-	-

3 Introduction to ASCE No. 79

ASCE's safety concept is based on the allowable stress intensity S defined as the minimum of either the minimum specified yield strength Re divided by 1.5 or the minimum specified tensile strength Rm divided by 2.4. Hence, it also accounts for the material's tensile strength, which becomes decisive for almost all steel grades investigated in this study and is the driving factor of ASCE's safety philosophy.

$$S = MIN \left[\frac{Re}{1.5}; \frac{Rm}{2.4} \right]$$

The guideline provides stress categories, so-called SI classifications, for parts typically found in penstocks and tunnel liners. These well-described stress categories allow a more precise assignment to allowable stress, which also accounts for local primary membrane and bending stress and for secondary stress. Moreover, introducing a local stress criterion answers the question of what exactly "local" means. Depending on the type of stress, the allowable stress categories are multiplied by stress increase factors. For "normal conditions" e.g., the general primary membrane stress (hoop stress in pipes) shall not exceed S , local primary membrane and/or bending stress in the vicinity of reinforcing girders and changes in direction shall not exceed 1.5-times S , and the combination of primary stress intensities with secondary stresses shall be the lesser of 3-times S or the minimum tensile strength (refer to Table 2). Thanks to this approach, the classification of finite element stress results is clearly defined and can be easily compared with the decisive allowable stress.

Table 2: Allowable stress intensities from ASCE manual No. 79

K factor or SI category	Normal conditions	Intermittent conditions	Emergency conditions
Increase Factor, K	1.0	1.33	1.5
General Primary Membrane, P_m	1.0S	1.33S ³	1.50S ²
Local Primary Membrane, P_l	1.5S	2.0S ³	2.25S ²
Primary Bending, P_b	1.5S	2.0S ³	2.25S ²
Local Primary Membrane Plus Primary Bending (P_l+P_b)	1.5S	2.0S ³	2.25S ²
Secondary (P_l+P_b+Q)	The lesser of f_1 or 3S	The lesser of f_1 or 3S	1

4 Reasons for a “harmonization”

Over the past decades, CECT was cited (amongst other common steel construction standards, like EN 1993) in almost all specifications dealing with the erection of new penstocks known to the authors. As shown in Table 3 (projects based on CECT safety philosophy), it proved well since these power plants’ penstocks are in operation and work without incidents. Nowadays, it is state-of-the-art, using finite element technique to evaluate stresses of critical, complex structures within the water conveyance system, such as bifurcators, manholes, gate housings, etc. (often referred to as “special parts”). Common practice and in agreement with the experts is to apply ASCE for these specific and numerically evaluated structures. Hence, nowadays, employer requirements, notably on European projects or projects where the consultants are European consulting companies, seek to use or mix both safety concepts. However, the problem occurs at the interface of these two different safety concepts. ASCE allows a more precise stress evaluation with corresponding stress increase factors for FE-evaluated special parts. On the other hand, CECT has proven to be more adequate and economical when analytically evaluating cylindrical pipe sections, which usually make up the majority of penstock steel tonnage (see Figure 1, deviation of curves for CECT concreted steel liner and ASCE). Therefore, if straight cylindrical pipes split into bifurcators, such interfaces have not yet been solved with a harmonized safety concept.

Table 3: CECT based project overview

Hydropower plant	Com-misioning date	Design company	Material	Penstock type	Diameter/ Thickness [mm]	Max. design head [m]
PSHP Nant de Drance/ <i>Switzerland</i>	2011	Andritz	S355ML/ S690QL1	Embedded	3000 to 7700/ 26 to 75	588
PSHP Gouvaes/ <i>Portugal</i>	2016	Andritz	S355ML/S460 ML/S620ML1/ S620QL1	Embedded	2800 to 6000/ 20 to 70	726
STEP Abdelmoumen/ <i>Morocco</i>	2018	Andritz	S355/S460/ S500/S690	Exposed/ Embedded	3600 to 5000/ 14 to 75	633
PSHP Hatta/ <i>UAE</i>	2019	Andritz	S500ML/ S620QL	Embedded/ Buried	3100 to 6200/ 22 to 75	198
PSHP Amfilochia/ <i>Greece</i>	ongoing	Andritz	S355/S460/ S690	Embedded	3550 to 7800/ 15 to 56	450
Linth-Limmern PSW/ <i>Switzerland</i>	2015	DSD Noell	S355ML/S460 ML/S500ML/ S690QL	Embedded	4200 to 4400/ 33 to 61	1060
Vianden PSW/ <i>Luxemburg</i>	2013	DSD Noell	S460ML	Embedded	4500/ 16 to 50	300
Burfell Extension/ <i>Iceland</i>	2018	DSD Noell	S355ML/ S500ML	Embedded	5200/ 24 to 45	158
KW Ritom/ <i>Switzerland</i>	ongoing	DSD Noell	S355N/S460M L/S690QL	Exposed	2000 to 2200/ 15 to 32	1014
Karahnjukar HPP/ <i>Iceland</i>	2007	DSD Noell	S460ML/ S690QL	Embedded	3400/ 25 to 58	1060

Ingula/ South Africa	2015	Whessoe	S550QL/ S690QL	Embedded	5100 to 3600/ 22 to 60	720
Pergau/ Malaysia	2003	Whessoe	Kawasaki Riverace 780	Embedded	4200/ 20 to 38	495
Nam Ngum 2/Laos	2009	Whessoe	P460ML1	Embedded	10150 to 5350/ 12 to 22	170
Nam Kong 3/Laos	2022	Whessoe	P355M	Embedded	4200/ 15 to 36	100

Fig. 1 shows the discrepancy between both concepts. The allowable general membrane stress (applicable to, e.g., hoop stress in straight cylindrical pipes) is plotted against the ratio of minimum specified yield strength (YS) and minimum specified tensile strength (TS) for plate thicknesses up to 100 mm and steel grades listed in Table 4. Since ASCE does not consider stress increase factors for different “types of penstocks,” the only curve provided here is historically based on the safety concept of the ASME B&PVC. This code, in turn, was created for pressure vessels, which are typically stand-alone structures comparable to exposed penstocks. Also, the European Pressure Vessel Code EN 13445-3 [6] is based on this “minimum requirements” criterion.

Hence, concreted steel liners based on CECT evaluation would be highly non-conservative in relation to ASCE recommendations. Interestingly, ASCE would underestimate “special parts” embedded in concrete with respect to CECT up to a ratio of 0.75.

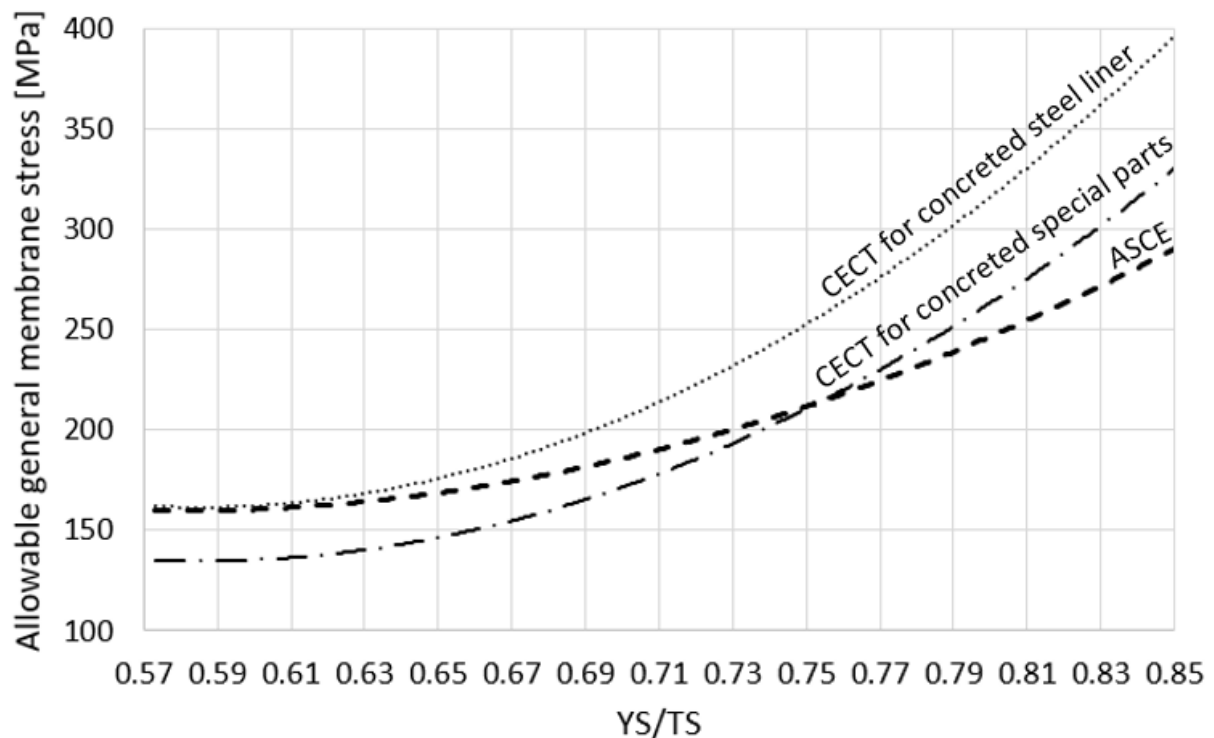


Fig. 1: Comparison between CECT and ASCE

The idea of the present paper is to propose a harmonized approach that attempts to combine the proven benefits of both guidelines and to eliminate the discrepancy.

5 Proposed harmonized safety concept

The strength analysis of a penstock is mainly based on stresses caused by internal design pressure. Concerning the evaluation technique (analytical/numerical), it is generally distinguished between steel liner shells made of cylindrical pipes (steel liner plates, SL) and special components (bifurcators, etc., SP). In the present paper, the black rectangular marked cases (see Table 1) depending on the “support” conditions have been investigated in detail.

The steel grades listed in Table 4 with an assumed plate thickness of 100 mm as an upper limit are analysed (bifurcator plates and their reinforcing girders/sickle plates often reach such dimensions, and consequently the standard values for yield- and tensile strength are reduced):

Table 4: Investigated steel grades for harmonized safety concept

	Re	Rm	YS/TS	Standard
	[MPa]	[MPa]		
S235JR/J0/J2	215	360	0.60	EN 10025-2
S275N/NL	235	370	0.64	EN 10025-3
S275JR/J0/J2	235	410	0.57	EN 10025-2
S275M/ML	245	350	0.70	EN 10025-4
P275NH/NL1/NL2	235	370	0.64	EN 10028-3
S355JR/J0/J2	315	470	0.67	EN 10025-2
S355N/NL	315	470	0.67	EN 10025-3
S355M/ML	325	440	0.74	EN 10025-4
P355N/NH/NL1/NL2	315	470	0.67	EN 10028-3
P355Q/QH/QL1/QL2	335	490	0.68	EN 10028-6
S420N/NL	360	520	0.69	EN 10025-3
S420M/ML	370	470	0.79	EN 10025-4
S460JR/J0/J2	390	550	0.71	EN 10025-2
S460N/NL	400	540	0.74	EN 10025-3
S460M/ML	400	500	0.80	EN 10025-4
S460Q/QL/QL1	440	550	0.80	EN 10025-6
P460NH/NL1/NL2	400	540	0.74	EN 10028-3
P460Q/QH/QL1/QL2	440	550	0.80	EN 10028-6
S500J0	450	580	0.78	EN 10025-2
S500M/ML	450	560	0.80	EN 10025-4
S500Q/QL/QL1	480	590	0.81	EN 10025-6
P500Q/QH/QL1/QL2	480	590	0.81	EN 10028-6
S550Q/QL/QL1	530	640	0.83	EN 10025-6
S620Q/QL/QL1	580	770	0.75	EN 10025-6
S690Q/QL/QL1	650	770	0.84	EN 10025-6
P690Q/QH/QL1/QL2	670	770	0.87	EN 10028-6

Based on the authors' experience, the most commonly used steel grades for penstocks range from S355 up to S690 (refer to Table 3).

Since CECT adjusts the safety factors against yield strength YS with respect to the penstock support condition and since ASCE also accounts for the tensile strength TS

of the material in the query of its stress intensity criterion, the idea is to maintain the proven CECT safety factors against yield strength but adjust the ASCE safety factor of 2.4 against tensile strength accordingly based on the fixed ratio of 2.4/2.0. The harmonized basic allowable stress intensities are now defined for each penstock support type in Table 5 (note: only for “normal operating conditions”):

Table 5: Minimum requirements criterion of harmonized safety concept

Concreted Steel Liner, $S_{SL.C}$	Exposed Steel Liner $S_{SL.E}$	Concreted Special Parts, $S_{SP.C}$	Exposed Special Parts, $S_{SP.E}$
$MIN \left[\frac{Re}{1.5}; \frac{Rm}{1.8} \right]$	$MIN \left[\frac{Re}{1.7}; \frac{Rm}{2.0} \right]$	$MIN \left[\frac{Re}{1.8}; \frac{Rm}{2.2} \right]$	$MIN \left[\frac{Re}{2.0}; \frac{Rm}{2.4} \right]$
with 1.8 = 1.5 · (2.4/2.0)	with 2.0 = 1.7 · (2.4/2.0)	with 2.2 = 1.8 · (2.4/2.0)	

In technical specifications for the design of mainly European penstocks, it is often required to limit the yield strength of the material to a value of 0.8-times the tensile strength if a ratio of YS/TS of 0.8 is exceeded. This is the case for high-tensile strength steels, used for highly pressurized sections, such as bifurcations in manifold sections. Although this requirement is not stated in any of the standards/guidelines known to the authors, it is also considered in the harmonized concept for reasons of conservativeness.

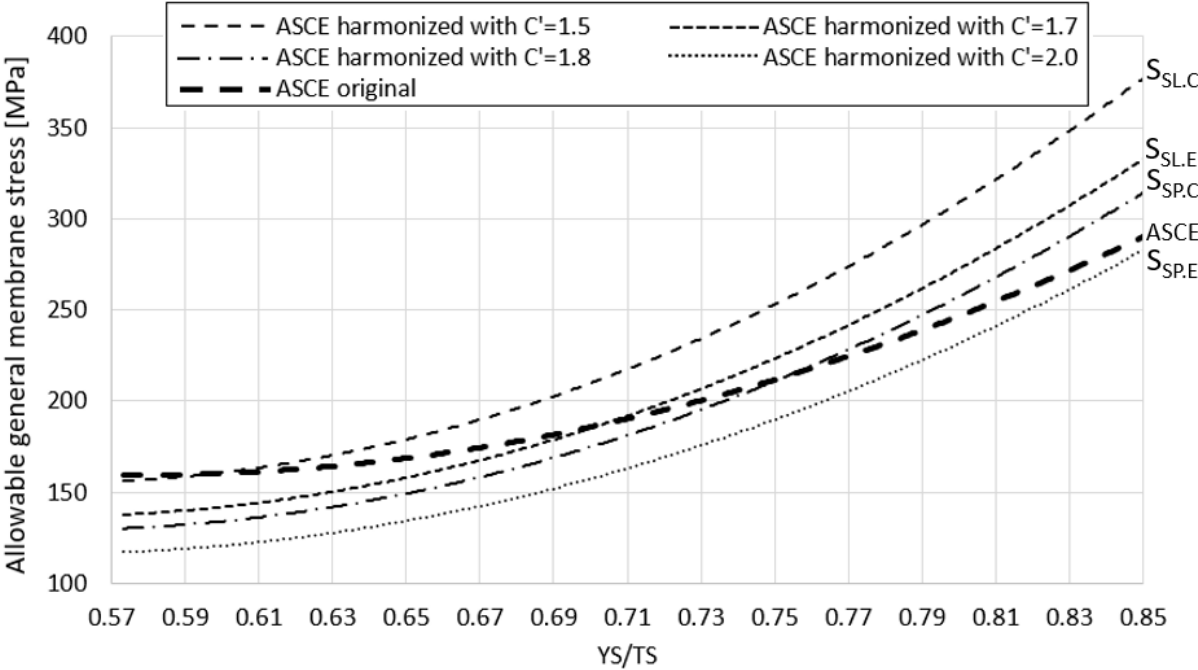


Fig. 2: Graphical representation of harmonized safety concept

The harmonized safety concept now accounts for the different support conditions of a penstock. For the exposed special parts it does not exceed ASCE criterion even up to a ratio of YS/TS = 0.85. These relationships are graphically depicted in Fig. 2.

With respect to the classification of stress categories, the proposed concept furthermore follows the rules given in ASCE for locally increased stress regions and for secondary stress regions. The locally increased stresses can easily be determined by using different evaluation techniques for assessing the so-called structural stress (a summary of these approaches is given in e.g. [7]), which can then be compared with the allowable locally increased stresses. By the way, the criterion “local” is also clearly defined in ASCE in order to differentiate it from global membrane stress.

The harmonization now enables a more accurate stress determination for complex structures where FEA is applied and where justification problems often arise as two different safety concepts collide at the “interface”. It also allows different support conditions to be taken into account.

The harmonized allowable stress intensities for primary global membrane stress (P_m), local membrane and/or bending stress (P_I+P_b , P_I , P_b) and for secondary stress (P_I+P_b+Q) are graphically depicted in Fig. 3 for normal operating conditions and YS/TS ratios between 0.57 and 0.85.

Instead of S , the formulae for $S_{SL,C}$, $S_{SL,E}$, $S_{SP,C}$ or $S_{SP,E}$ (Table 5) should be used to determine the basic allowable stress intensity. The basic stress intensity is then multiplied by 1.5 for local stress. For secondary stress the lesser of 3-times the basic stress intensity or the minimum specified tensile strength is used.

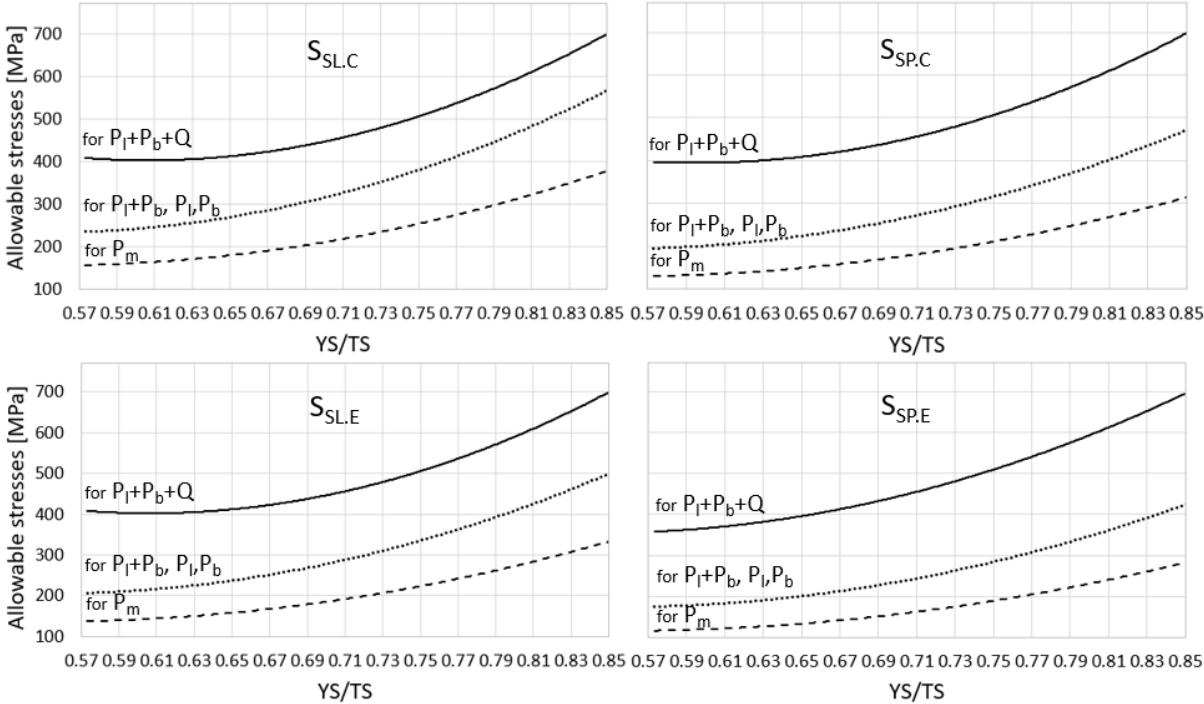


Fig. 3: Allowable stress intensities for exposed and concreted steel liners and special parts

6 Conclusion and outlook

The present paper discusses the proposal of a harmonized safety concept for overcoming the discrepancy when evaluating stress at the interface between analytical and numerical approaches. Often, this difficulty is ignored, or the analytically based concept of CECT is used for complex finite element models, which is far too conservative compared with local stress approaches, as ASCE manual No. 79 provides. On the other hand, evaluating the entire steel liner based on ASCE's allowable global membrane stress limit would be uneconomical and far too conservative.

Regarding high-strength steels (steel grades with high strength but low toughness), there is the fear of brittle fracture due to their little ability to absorb energy before sudden failure. Therefore, the yield strength is often specified to be limited to 0.8-times the tensile strength for YS/TS ratios > 0.8 . Recent research [8] showed that even larger YS/TS ratios (> 0.94) result in a marginally increased local strain with a small risk for ductile failure.

CODETI, the little-known successor to CECT, takes tensile strength into account in addition to yield strength and uses a similar "minimum requirements" criterion to ASCE. However, for concreted steel liners it is even more conservative as it suggests a safety of 2 against the tensile strength instead of 1.8 suggested here.

Considering all of these it would make sense to intensively rethink our penstock safety concepts. The importance of tensile strength with the new findings on the material behaviour, the general support conditions of penstocks and economic, safe but not overconservative design should find their way into our considerations. It should also be noted that penstock failures in the past have often been related to pressure loads other than only internal water pressure, such as buckling, fatigue relevant pressure variations and weld/material quality issues.

The authors of this paper understand they can only provide their experiences from a computational perspective. An intensive exchange with experts in the areas of material properties and metallurgy is essential. But at least the article can serve as discussion material for the revision of our penstock design philosophies.

References

- [1] C. Pollak-Reibenwein, B. Neugschwandtner, A case study of a high strength steel design: Application of different safety concepts and the resulting impacts on a bifurcation, *Book of Full Papers Symposium Hydro Engineering*, p. 2337-2348, ICOLD conference, Austria, 2018.
- [2] *CECT Recommendations for the design, manufacture and erection of steel penstocks of welded construction for hydro electric installations*, Comité Européen

de la Chaudronnerie et de la Tolerie, edition 1979, including modifications 1984, SNCT Publications, Paris.

- [3] *ASME BPVC (Boiler & Pressure Vessel Code), Section VIII Rules of Construction for Pressure Vessels, Division 2 Alternative Rules* (2015), The American Society of Mechanical Engineers, New York.
- [4] *ASCE Manuals and Reports on Engineering Practice, No.79, Steel Penstocks*, 2nd Edition (2012), American Society of Civil Engineers, Reston, VA.
- [5] *CODETI Division 3, Code for Construction of Penstocks*, Edition 2014, SNCT Publications.
- [6] *DIN EN 13445-3, Unfired pressure vessels – Part 3 : Design*, (2021)
- [7] C. Pollak-Reibenwein, E. Akgun, Fatigue Weld Assessment in FEA by means of local stresses, *Proceedings of 10th ICOLD European Club Symposium*, Turkey, 2016.
- [8] S.F.P.M. Obers, J. J. Overal, Wei J. Wong, C. L. Walters, The effect of the yield to tensile strength ratio on stress/strain concentrations around holes in high-strength steels, *Marine Structures* 84 (2022).

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