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Division I

BEHAVIOR OF PRESTRESSED CONTAINMENT WALL STRUCTURES WITH LINER CONSIDERING LONG TERM LOSSES

Christian Lang[1], **Burkhard Wienand**[2]

[1] Dr.-Ing., Consulting Engineer, Im Erb 15, 67487 Maikammer, Germany (christian.lang@ibb-lang.de)
[2] Dr.-Ing., AREVA NP, Kaiserleistraße 29, 63067 Offenbach, Germany (burkhard.wienand@areva.com)

ABSTRACT

Currently, nuclear power plants of third+ generation are being erected world wide. One special representative of these third+ generation NPPs is AREVA's EPR^{TM}. Heart of this power plant is the reactor building with its prestressed inner containment. This containment consists of a cylindrical shell lower part and an upper dome part. Sturctural integrity and leaktightness in case of accidents shall be maintained by two means: prestressing of concrete in order to prevent cracking of concrete and steel liner attached to the inner containment surface by stud connectors.

One special feature of this containment layout concept is that full compression at the end of lifetime is maintained. Mean concrete section stress shall be compressive in membrane zones at the end of lifetime in normal operating conditions including pressure test. However, this design criterion implies that a very high level of prestressing must be provided at the beginning of lifetime to compensate losses due to creep & shrinkage of concrete. Further, the presence of the steel parts with their stiffness contribution result in a rearrangement of internal prestressing forces from the concrete to steel parts including liner with all its drawbacks (buckling of thin liner plate due to compressive forces).

Thus, in this paper a study will be conducted where the level of prestressing is reduced while the missing prestressing reinforcement will be substituted by regular rebars with equivalent section. It can be shown that the ultimate pressure resistance level is maintained while the section stress distribution is positively influenced. This method is known as limited (tensile stresses up to tensile strength of concrete allowed) or partial prestressing (tensile stresses exceed tensile strength of concrete) which is commonly known in bridge design and might be worth spending thoughts onto in containment design since leak tightness can be fully assigned to the liner. The behavior of full and partial prestressed containments is shown and discussed in this paper.

CONTAINMENT LAYOUT

The layout of the EPR^{TM} containment is shown in Figure 1. At its inner surface, the containment is equipped with a thin metallic liner which is attached to the concrete wall by shear studs in order to ensure leak tightness. The structure consists of 3 parts which are indicated in the following:

	Cylinder part	
-	Inside radius	23.400 m
-	Thickness	1.300 m
-	Upper level	43.917 m
-	Lower level	-2.300 m

	Gusset (connection to common base slab)	
-	Upper level	-2.300 m
-	Lower level	-7.800 m
-	Upper inside radius	23.400 m
-	Lower inside radius	20.925 m

Dome

- Toric part, inside radius 8.000 m

- Dome spherical part
  Inside radius 32.000 m
  Thickness 1.000 m
  Level of dome centre 57.509 m

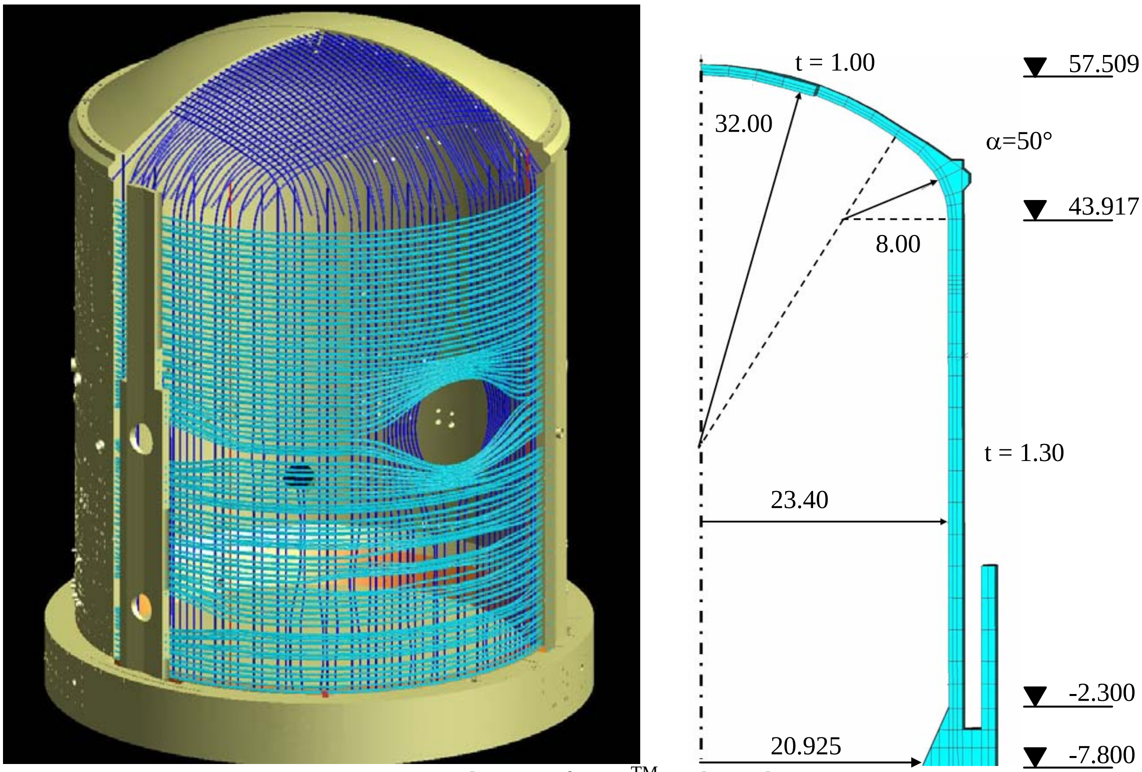

Figure 1. Containment layout of EPR^{TM} with tendons.

TENDON LAYOUT

The current design of standard EPR^{TM} provides a prestressing system which consists of the following tendon arrangement:

Horizontal prestressing (cylinder)	119 hoop tendons (360° arrangement) each tendon anchored at both sides of a buttress
Pure vertical tendons (cylinder)	47 pure vertical tendons anchored in tendon gallery below base slab and at dome girder
Gamma tendons (cylinder and dome)	104 gamma tendons anchored in tendon gallery below base slab and at opposite side of dome girder

This tendon arrangement leads to a mean vertical distance of 65 cm of hoop tendons. Horizontal tendons are arranged in two layers, the outer layer is fully occupied (tendon spacing 65 cm) while at the inner horizontal tendon layer only every second tendon is occupied (tendon spacing 130 cm). Mean distance of vertical tendons and gamma tendons in cylinder part is given by 2x24.05 / 151 = 1.00 m. Further, in standard dome sections the tendon arrangement leads to an orthogonal mesh with distance 0.725 m. Tendons with 54 strands each of cross section 150 mm² (thus, in total 54x1.5 = 81 cm²) and characteristic strength $f_{p0,1k}$ / f_{pk} = 1653 MN/m² / 1860 MN/m² are used.

Figure 2. Prestressing duct and reinforcement arrangement in cylinder and dome part of EPR^{TM}.

INITIAL PRESTRESS

Initial prestressing is done with 0.8 f_{pk} = 1488 MN/m². Computing all losses due to anchorage slip and friction of tendon in ducts, this leads to the following mean stresses and forces in tendons. The full prestressing values apply for standard EPR^{TM} design.

Full prestressing (100 %)

Hoop direction	σ_p = 985 MN/m²	F_p = 98.5x81x1.5/0.65 = 18412 kN/m
Vertical direction	σ_p = 1350 MN/m²	F_p = 135x81x151/1.00 = 10935 kN/m
Dome center	σ_p = 1235 MN/m²	F_p = 123.5x81x/0.725 = 13798 kN/m

Partial prestressing (66.7%) by reduction of installed tendon section and substitution by rebars

Hoop direction	σ_p = 985 MN/m²	F_p = 18412x2/3= 12275 kN/m
Vertical direction	σ_p = 1350 MN/m²	F_p = 10935x2/3 = 7290 kN/m
Dome center	σ_p = 1235 MN/m²	F_p = 13798x2/3 = 9199 kN/m

Partial prestressing (33.3%) by reduction of installed tendon section and substitution by rebars

Hoop direction	σ_p = 985 MN/m²	F_p = 18412/3= 6137 kN/m
Vertical direction	σ_p = 1350 MN/m²	F_p = 10935/3 = 3645 kN/m
Dome center	σ_p = 1235 MN/m²	F_p = 13798/3 = 4599 kN/m

LONG TERM BEHAVIOR OF CONCRETE – CREEP & SHRINKAGE

Creep and shrinkage characterize long term behavior of concrete. Shrinkage is independent of loading while creep depends on the level of concrete stress which means the higher the prestress the higher the creep effect. Taking into account creep and shrinkage laws of EN1992-2 with some slight modifications concerning biaxial state of compression which applies for the containment, the following values are obtained.

In Table 1, the corresponding values for the prestressed containment with different levels of prestressing are given. It is obvious while shrinkage remains constant, the creep effect decreases with decreasing prestressing level.

Table 1: Creep and Shrinkage of concrete

	autogeneous shrinkage		drying shrinkage		basic creep			drying creep	
	cylinder	dome	cylinder	dome	cylinder		dome	Cylinder	dome
					h	v			
	[µm / m]		[µm / m]		[µm / m]			[µm / m]	
full prestress	0	24	365	513	309	186	282	278	444
2/3 prestress	0	24	365	513	206	124	188	185	296
1/3 prestress	0	24	365	513	103	62	94	93	148
no prestress	0	24	365	513	0	0	0	0	0

SECTION STRESSES AT BEGIN AND END OF LIFETIME

The following two situations will be analyzed: Section stress distribution (tendons, concrete, rebars, liner) at the begin and end of lifetime. The stresses are obtained by section equilibrium iteration.

a) begin of lifetime: initial prestress of tendons (and thus initial strain difference) is given, section stress distribution must be found by strain iteration while the sum of forces throughout the whole section must be zero (no resulting force)

b) end of lifetime: prestressing tendons, rebars and liner can not follow the shortening of concrete. So, all metallic elements are compressed and the concrete is in tension to remain section compatibility, Rüsch et al. (1976). Again, all external forces are zero in this situation. The stresses obtained due to creep and shrinkage are superposed with stresses at begin of lifetime.

For the calculations, the following assumptions apply for the fully prestressed concrete cylinder and dome section according to Table 2. Hereby, section values of full prestressed containment are taken from EPR^{TM} basic design. The level of prestressing is then continuously reduced to 2/3, 1/3 and 0 by decreasing the tendon section and substituting this section with corresponding rebar section in the middle layer.

$$\Delta A_s = \Delta A_p \cdot f_{pk} / f_{uk} = \Delta A_p \cdot 1860 / 550 \qquad (1)$$

Table 2: Section properties of cylinder and dome

Full Prestress	Cylinder horizontal	Cylinder vertical	dome
Concrete section	1.30 m	1.30 m	1.00 m
Liner section*	(7 mm) 70 cm²/m	(7 mm) 70 cm²/m	(9 mm) 90 cm²/m
Inner rebars	22.6 cm²/m	23.8 cm²/m	19.9 cm²/m
Outer rebars	57.6 cm²/m	58.1 cm²/m	50.7 cm²/m
Middle rebars	-	-	-
Tendon layer 1	62.3 cm²/m	81.0 cm²/m	111.7 cm²/m
Tendon layer 2	124.6 cm²/m	-	
2/3 Prestress	Cylinder horizontal	Cylinder vertical	dome
Concrete section	1.30 m	1.30 m	1.00 m
Liner section*	(7 mm) 70 cm²/m	(7 mm) 70 cm²/m	(9 mm) 90 cm²/m
Inner rebars	22.6 cm²/m	23.8 cm²/m	19.9 cm²/m
Outer rebars	57.6 cm²/m	58.1 cm²/m	50.7 cm²/m
Middle rebars	210.7 cm²/m	91.3 cm²/m	125.9 cm²/m
Tendon layer 1	41.5 cm²/m	54.0 cm²/m	74.5 cm²/m
Tendon layer 2	83.1 cm²/m	-	
1/3 Prestress	Cylinder horizontal	Cylinder vertical	dome
Concrete section	1.30 m	1.30 m	1.00 m
Liner section*	(7 mm) 70 cm²/m	(7 mm) 70 cm²/m	(9 mm) 90 cm²/m
Inner rebars	22.6 cm²/m	23.8 cm²/m	19.9 cm²/m
Outer rebars	57.6 cm²/m	58.1 cm²/m	50.7 cm²/m
Middle rebars	421.4 cm²/m	182.6 cm²/m	251.8 cm²/m
Tendon layer 1	20.8 cm²/m	27.0 cm²/m	37.2 cm²/m
Tendon layer 2	41.5 cm²/m	-	
No Prestress	Cylinder horizontal	Cylinder vertical	Dome
Concrete section	1.30 m	1.30 m	1.00 m
Liner section*	(7 mm) 70 cm²/m	(7 mm) 70 cm²/m	(9 mm) 90 cm²/m
Inner rebars	22.6 cm²/m	23.8 cm²/m	19.9 cm²/m
Outer rebars	57.6 cm²/m	58.1 cm²/m	50.7 cm²/m
Middle rebars	632.2 cm²/m	273.9 cm²/m	377.8 cm²/m
Tendon layer 1	-	-	-
Tendon layer 2	-	-	

(* Liner section including equivalent contributing stiffener section)

Table 3: Stress distribution in cylinder and dome – 100% prestress

	Cylinder 100 % Prestress				Dome 100 % Prestress			
	Begin of Lifetime		End of Lifetime		Begin of Lifetime		End of Lifetime	
	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v
concrete	-13.3	-8.0	-9.2	-5.1	-12.7	-12.7	-6.7	-6.7
liner	-78.2	-50.7	-282.6	-248.7	-76.9	-76.9	-350.0	-350.0
inner rebars	-66.1	-29.8	-220.1	-175.2	-57.2	-57.2	-260.4	-260.4
outer rebars	-66.1	-29.8	-220.1	-175.2	-57.2	-57.2	-260.4	-260.4
middle rebars	-66.1	-29.8	-220.1	-175.2	-57.2	-57.2	-260.4	-260.4
inner tendons	985.0	1350.0	838.7	1211.8	1235.0	1235.0	1042.0	1042.0
outer tendons	985.0	1350.0	838.7	1211.8	1235.0	1235.0	1042.0	1042.0

Table 4: Stress distribution in cylinder and dome – 66.7 % prestress

	Cylinder 66.7 % Prestress				Dome 66.7 % Prestress			
	Begin of Lifetime		End of Lifetime		Begin of Lifetime		End of Lifetime	
	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v
concrete	-8.3	-5.2	-3.9	-2.4	-8.0	-8.0	-2.0	-2.0
liner	-48.6	-32.8	-200.5	-186.5	-48.7	-48.7	-257.1	-257.1
inner rebars	-40.7	-19.8	-153.2	-134.8	-36.2	-36.2	-191.3	-191.3
outer rebars	-40.7	-19.8	-153.2	-134.8	-36.2	-36.2	-191.3	-191.3
middle rebars	-40.7	-19.8	-153.2	-134.8	-36.2	-36.2	-191.3	-191.3
inner tendons	985.0	1350.0	878.2	1240.8	1235.0	1235.0	1087.7	1087.7
outer tendons	985.0	1350.0	878.2	1240.8	1235.0	1235.0	1042.0	1042.0

Table 5: Stress distribution in cylinder and dome – 33.3 % prestress

	Cylinder 33.3 % Prestress				Dome 33.3 % Prestress			
	Begin of Lifetime		End of Lifetime		Begin of Lifetime		End of Lifetime	
	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v
concrete	-3.9	-2.5	0.0	0.0	-3.8	-3.8	1.5	1.5
liner	-22.8	-15.9	-129.4	-129.1	-23.2	-23.2	-173.7	-173.7
inner rebars	-18.9	-9.8	-96.3	-96.0	-17.3	-17.3	-129.3	-129.3
outer rebars	-18.9	-9.8	-96.3	-96.0	-17.3	-17.3	-129.3	-129.3
middle rebars	-18.9	-9.8	-96.3	-96.0	-17.3	-17.3	-129.3	-129.3
inner tendons	985.0	1350.0	911.5	1268.2	1235.0	1235.0	1128.6	1128.6
outer tendons	985.0	1350.0	911.5	1268.2	1235.0	1235.0	1128.6	1128.6

Table 6: Stress distribution in cylinder and dome – no prestress

	Cylinder no prestress				Dome no prestress			
	Begin of Lifetime		End of Lifetime		Begin of Lifetime		End of Lifetime	
	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v	σ_h	σ_v
concrete	0.0	0.0	2.9	2.0	0.0	0.0	4.2	4.2
liner	0.0	0.0	-66.6	-75.3	0.0	0.0	-98.5	-98.5
inner rebars	0.0	0.0	-47.1	-58.5	0.0	0.0	-73.3	-73.3
outer rebars	0.0	0.0	-47.1	-58.5	0.0	0.0	-73.3	-73.3
middle rebars	0.0	0.0	-47.1	-58.5	0.0	0.0	-73.3	-73.3
inner tendons	-	-	-	-	-	-	-	-
outer tendons	-	-	-	-	-	-	-	-

In the dome center, an axxissymmetric state of stress and strain is given with $\sigma_h = \sigma_v$ due to symmetry axis conditions. It has to be noted that a biaxial material law for both concrete and liner must be used; otherwise results will not reflect reality in a proper way.

$$\sigma_h = E / (1-\nu^2) \cdot (\varepsilon_h + \nu \cdot \varepsilon_v) \tag{2a}$$

$$\sigma_v = E / (1-\nu^2) \cdot (\nu \cdot \varepsilon_h + \varepsilon_v) \tag{2b}$$

Considering a test pressure of 500 kN/m², the following mean concrete stresses due to p = 500 kN/m² are obtained, differences are due to different ideal concrete section.

$$A_i = A_c + (E_s/E_c - 1) \cdot A_s + (E_l / E_c - 1) \cdot A_l + (E_p / E_c - 1) \cdot A_p \tag{3}$$

Table 7: Concrete stresses due to test pressure p = 500 kN/m² with A_i section

100% prestressing	σ_h = 7.6 MN/m²	σ_v = 4.0 MN/m²	dome σ = 6.6 MN/m²
66.7% prestressing	σ_h = 7.0 MN/m²	σ_v = 3.8 MN/m²	dome σ = 6.2 MN/m²
33.3% prestressing	σ_h = 6.5 MN/m²	σ_v = 3.7 MN/m²	dome σ = 5.8 MN/m²
No prestressing	σ_h = 6.0 MN/m²	σ_v = 3.6 MN/m²	dome σ = 5.5 MN/m²

From the results, it can be seen that in the case of 100% prestressing the concrete stresses are fully in compression even at the end of lifetime. However, a very high level of prestressing at begin of lifetime is required to compensate the losses due to creep & shrinkage. Further, the liner is under biaxial compression while its yield limit is already reached (f_{yk} = 275 MN/m² for P275NL2) with all corresponding problems (problem of local liner buckling), see Table 3.

Thus, it should be worth while spending thoughts on reducing the level of prestressing and not to fulfill the design criterion full compression at end of lifetime under test pressure, since leak tightness is ensured by the metallic liner anyway. E.g. by reducing the level of prestressing to 66.7%, full prestress at begin of lifetime is still valid while at the end of lifetime mean tensile stresses occur which are actually smaller than the mean tensile strength f_{ctm} = 4.1 MN/m² for concrete C50/60. This concept is well known especially in bridge design as limited prestressing according to design code DIN 4227 which is now substituted by EN 1992. In this case, the liner does not yield at end of lifetime and the prestressing losses due to creep are smaller than for 100% prestressing.

The same trend can be observed by further reducing the level of prestressing down to 33.3%. Here, the stresses due to test pressure at end of lifetime exceed the tensile strength of concrete. This is known as partial prestressing. Concrete will crack under test pressure situation. However, cracks will be compressed elastically when test pressure is removed.

ULTIMATE PRESSURE RESISTANCE

The ultimate pressure resistance of the containment in current zones (assumption of membrane behavior, no locks or hatches) is neither influenced by the level of prestressing nor creep & shrinkage. It is only depending on the amount of steel in the cross section which can withstand the pressure situation.

Full presstress
Cylinder horizontal $p \cdot R = f_l \cdot A_l + A_s \cdot f_u + A_p \cdot f_p$
$p = (320 \cdot 0.007 + 80.2e^{-4} \cdot 550 + 186.9e^{-4} \cdot 1860)/24.05 = 1.72\ \mathrm{MN/m^2}$
Cylinder vertical $p \cdot R/2 = f_l \cdot A_l + A_s \cdot f_u + A_p \cdot f_p$
$p = (320 \cdot 0.007 + 81.9e^{-4} \cdot 550 + 81.0e^{-4} \cdot 1860)/24.05 \cdot 2 = 1.81\ \mathrm{MN/m^2}$
Dome center $p \cdot R/2 = f_l \cdot A_l + A_s \cdot f_u + A_p \cdot f_p$
$p = (320 \cdot 0.009 + 70.6e^{-4} \cdot 550 + 111.7e^{-4} \cdot 1860)/32.5 \cdot 2 = 1.69\ \mathrm{MN/m^2}$

66.7% prestress
Cylinder horizontal $p = (320 \cdot 0.007 + 290.3e^{-4} \cdot 550 + 124.6e^{-4} \cdot 1860)/24.05 = 1.72\ \mathrm{MN/m^2}$
Cylinder vertical $p = (320 \cdot 0.007 + 173.2e^{-4} \cdot 550 + 54.0e^{-4} \cdot 1860)/24.05 \cdot 2 = 1.81\ \mathrm{MN/m^2}$
Dome center $p = (320 \cdot 0.009 + 196.5e^{-4} \cdot 550 + 74.5e^{-4} \cdot 1860)/32.5 \cdot 2 = 1.69\ \mathrm{MN/m^2}$

33.3% prestress
Cylinder horizontal $p = (320 \cdot 0.007 + 501.6e^{-4} \cdot 550 + 62.3e^{-4} \cdot 1860)/24.05 = 1.72\ \mathrm{MN/m^2}$
Cylinder vertical $p = (320 \cdot 0.007 + 173.2e^{-4} \cdot 550 + 54.0e^{-4} \cdot 1860)/24.05 \cdot 2 = 1.81\ \mathrm{MN/m^2}$
Dome center $p = (320 \cdot 0.009 + 196.5e^{-4} \cdot 550 + 74.5e^{-4} \cdot 1860)/32.5 \cdot 2 = 1.69\ \mathrm{MN/m^2}$

No prestress
Cylinder horizontal $p = (320 \cdot 0.007 + 712.4e^{-4} \cdot 550)/24.05 = 1.72\ \text{MN/m}^2$
Cylinder vertical $p = (320 \cdot 0.007 + 355.8e^{-4} \cdot 550)/24.05 \cdot 2 = 1.81\ \text{MN/m}^2$
Dome center $p = (320 \cdot 0.009 + 448.4e^{-4} \cdot 550)/32.5 \cdot 2 = 1.69\ \text{MN/m}^2$

By substituting the prestressing tendons with equivalent rebar section taking into account the ultimate strength ratio f_{pk} / f_{uk} = 1860/550, the same ultimate pressure resistance is obtained. The advantage in prestressing can be seen in the utilization of higher steel grades (in this case $f_{p0,1k}$ / f_{pk} = 1653 / 1860) and in a positive influence on the serviceability limit state. The ultimate capacity is also not influenced by creep & shrinkage which results only in a decrease of strain difference between prestressing steel and concrete and thus has only effects on the serviceability limit state.

CONCLUSIONS

The EPR™ design provides a prestressing concept which ensures mean compressive concrete stresses in case of test pressure at the end of lifetime. Additional, a metallic liner is attached to the inner surface to provide leaktightness. However beside its advantages (especially the utilization of high steel grades), prestressing has one main drawback: creep & shrinkage reduce the initial tendon forces and prestresses the liner which tends to local buckling under high biaxial compression. So, a very high amount of prestressing tendons and a very high level of prestressing are needed just to ensure this design criterion. Since leaktightness is ensured by the liner, the prestressing level can be reduced without reduction of the ultimate pressure capacity but just by influencing the serviceability limit state. In this case, the SLS state is mainly characterized by the pressure level at which cracking of concrete takes place. Here, limited tensile stresses might be allowed also accounting for high concrete tensile strength (concept of limited or partial prestressing) with the corresponding effect of reduction of prestressing forces. The ultimate pressure capacity itself is only influenced by the installed amount of steel to balance the internal membrane forces.

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