DESIGN CRITERIA FOR HOOPS OF CONCRETE STAVE SILOS

J. C. Jofriet and H. S. Kleywegt

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1

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Present design procedures of stave tower silos do not adequately deal with the tension that must be present in the hoops to ensure a homogeneous cylindrical shell structure capable of resisting horizontal loads such as wind. Loss of tension in the hoops from friction between the staves and the hoops, from elastic shortening, and from creep and shrinkage are not usually accounted for in a quantitative manner. This paper presents a number of design criteria for the structural design of concrete stave structures. These criteria are based on prestressed concrete design principles and recognize that prestress losses will reduce the amount of tension put in the hoops at the time of erection. The proposed design criteria have been applied to an example problem. The results show that with proper measures to minimize losses in hoop tension, the criterion of some residual compressive stress in the stave wall at full load can be achieved with few or no extra hoops.

INTRODUCTION

Prestress losses in stave silos were identified by the authors (Kleywegt and Jofriet 1979). None of the available design codes or standards for farm silos deal with prestress losses explicitly even though they have an important effect on the strength and rigidity of stave silos. Loss of tension of the hoops can change a more or less homogeneous cylindrical shell structure into a large number of individual concrete components, stacked up but incapable of acting together. When this happens, a silo is very susceptible to wind when empty.

In this paper, the earlier recommendations (Kleywegt and Jofriet 1979) and findings by Kleywegt (1978) are used to formulate a comprehensive set of design criteria that will provide a more rational stave silo design approach. The proposed design criteria have been formulated with the view that farm stave silos built at present provide an economical silage storage structure or liquid manure tank. Therefore, improvements in the present system rather than a complete redesign is suggested.

The design criteria and recommendations are illustrated with a stave silo design example.

HOOP STRENGTH CRITERION

The minimum cross-sectional area of the hooping must be determined such as to prevent failure from horizontal internal silo pressure. This criterion can be stated as follows:

> The ultimate circumferential tensile strength of the hoops shall be equal to or greater than the tension in the hoops caused by the internal horizontal pressure, times an appropriate load factor.

Using the concrete code CSA A23.3 (1977) as a basis, an appropriate load factor for silage pressure would be 1.7 because of its similarity to soil pressure. If the silo is to be designed for liquid pressure, a load factor of 1.4 would be more appropriate. In the case of low human occupancy farm applications, these load factors may be multiplied by an importance factor of 0.8 (Standing Committee 1977).

The strength of the hooping is subject to a capacity reduction factor. At present, steel hoops do not have a minimum guaranteed yield strength. In view of this, a capacity reduction factor of 0.8 is suggested. Thus, the overall factor separating strength and effect of load would be 1.7 for farm silage silos and 1.4 for liquid manure tanks; in terms of working stress design, the equivalent allowable stresses in the hoops would be $0.59 f_y$ and $0.71 f_y$, respectively.

The Ontario Silo Association Standard (1974) specifies an allowable stress of $0.6 f_y$ for tower silo hoops. This requirement results in a hoop spacing, s, of:

$$s \leq \frac{1.2 f_y A_s}{LD} \tag{1}$$

where f_y is the hoop's yield strength, A_s is the cross-sectional area of a hoop, L the internal horizontal wall pressure, and D the silo diameter. The internal horizontal pressure, L, may be determined from the Canadian Farm Building Code (CFBC 1977) formula:

$$L = 4.8 + 0.58\, h\, D^{0.55} \tag{2}$$

in which L is in kN/m^2, D is in meters and h is the depth, in meters, at which L is desired, measured from the top of the silo.

HOOP TENSION SPECIFICATIONS

The hoops can satisfy the above strength criterion without being prestressed as long as the staves are there to transfer the internal pressure to the hoops. However, besides providing ultimate strength for resisting the internal pressure, hoops must provide adequate prestress in the staves to allow them to act together through friction in the vertical joints and thus make the silo into a more or less homogeneous cylindrical structure. Lack of integrity can lead to local or overall failure of the silo when subjected to high wind loads and to problems if uneven filling causes asymmetric internal loading. Furthermore, a homogeneous structure is a necessary requirement if the silo is going to be used for the storage of liquids or if the storage structure is an oxygen-limiting silo. In these cases the stave construction would probably be used in combination with monolithic concrete, such as gunite or shotcrete.

The design criterion that encompasses all these requirements is that

> the prestress in the hoops, after all losses, be of such magnitude that the silo wall remains in circumferential compression at full service load.

Assuming a nominal amount of compression at full load and strain compatability between hoops and staves, the required prestress in the hoops after losses, T, to satisfy this design criterion may be expressed by:

$$T \geq 0.5\, LsD \left(\frac{A_c}{A_c + nA_s}\right); A_c = ts \tag{3}$$

in which n is the modular ratio and t is the thickness of the silo wall. Since nA_s is generally small compared to A_c, Eq. 3 can be reduced approximately to:

$$T \geq 0.5 LsD \tag{4}$$

Substituting the maximum spacing from Eq. 1 into Eq. 4 gives:

$$T \geqslant 0.6 f_y A_s \qquad (5)$$

The CFBC (1977) requires that concrete stave silo hoops be tensioned to 60% of their yield strength at the time of erection. Equation 5 indicates that this requirement is equivalent to the design criterion stated earlier if prestress losses are neglected.

The CFBC (1977) makes no specific allowance for hoop tension losses. However, it will be seen later that tension losses amount to 25–50% of the initial hoop tension even if all precautions are taken to minimize them. This means that if the CFBC requirements are adhered to, only about 30–45% of the yield strength remains as effective prestress.

There are other problems to be considered before the criterion related to prestress in hoops (Eq. 3 or 4) can be adopted for silos in which the concrete stave is the only wall component. The problems are concerned with the concrete staves.

Although by Eq. 5 the prestress force in the hoops is only a function of the yield strength of the hoop steel and of the cross-sectional area of a hoop, the prestress induced in the concrete staves is a function of the spacing of the hoops. The compressive stress in the concrete is highest when the tension in the hoop is highest, i.e. initial tension, and when the internal pressure, L, is zero. Then:

$$f_{c_i} = \frac{T_i}{A_c} \qquad (6)$$

in which f_{c_i} and T_i are the initial concrete compressive stress and initial hoop tensile force at time of tensioning, e.g. before any losses have taken place. Assuming t to equal 65 mm, one 14.3-mm diameter hoop per stave (s = 762 mm) might typically yield f_{c_i} = 0.7 MPa; with four hoops per stave, however, and all other parameters unchanged, this concrete stress would be 2.8 MPa.

In one of the last tests carried out on a 4.9-m test silo (Kleywegt 1978), strain readings on hoops indicate that the average initial tension for one of the hoops (No. 7) was 31.7 kN. All other hoops (3 hoops per stave) received similar tensions. The calculated concrete compressive stress then is approximately 1.9 MPa. At this stress, 25% of the staves had cracked horizontally over the full width of the stave. The main cause for the cracking was large vertical bending stresses in the staves, most of which were found to have long sides that were not perfectly straight. This resulted in two-point contact with the adjacent staves and bending in the plane of the staves (Kleywegt 1978).

Although the authors do not suggest that imperfect staves should govern the design of stave silos, at present horizontal cracking of staves is a real problem. It is possible that this problem can be corrected with improved quality control. The problem can certainly be alleviated by grouting the joints before stressing the hoops. This would require important and costly changes in the present erection procedures.

A further problem that limits the amount of compressive stress that a silo wall can be subjected to is buckling due to high circumferential compressive stresses. Sadler (1972) provided guidelines for joint designs that will improve the silo wall stiffness. However, a relationship between hoop tension and stave geometry, and circumferential buckling is not available. No buckling occurred in the test carried out by Kleywegt (1978) at the maximum concrete stress estimated to be 2 MPa.

In view of the above considerations the hoop tension criterion proposed earlier in this section has to be complemented by restriction on concrete compressive stress when the silo wall consist of staves only. The following criterion is proposed for a stave silo 5 m diameter and less:

The initial prestress in the hoops shall (a) be limited to 80% of the hoop's yield strength and (b) provide in the staves a concrete compressive stress not exceeding 2 MPa.

The (b) part of this criterion is based on stresses obtained by Kleywegt (1978) in a 4.88-m diameter silo. Further research is required before extrapolation to larger silos can be recommended. For silo walls where the staves are augmented by monolithic concrete there is no problem. The thickness of the monolithic concrete can be selected to provide adequate stiffness and strength to prevent buckling and cracking. The American Concrete Institute Standard by ACI Committee 344 (1970) can be used as a guide.

HOOP DESIGN FOR TOWER SILOS

In this section the criteria of the previous section are reviewed in light of experience with tower silos. Considering the aboveground portion of the structure, wind loading is transferred to the foundation mainly by cantilever beam action. This results in "horizontal" shear in the vertical joints. Insufficient compression between adjacent staves can lead to the type of shear failure indicated Fig.

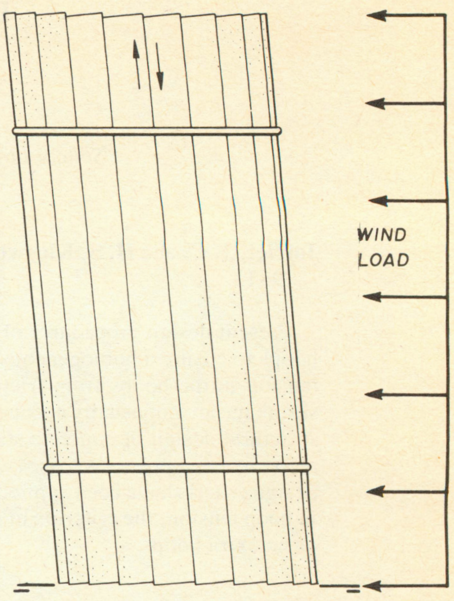

Figure 1. Shear failure in vertical joints of a stave tower silo due to wind loading.

1. The hoop tension required to prevent this shearing in the vertical joints can be determined as:

$$T \geqslant \frac{2hsQ}{\mu_c \pi} \qquad (7)$$

where Q is the wind loading per unit of area and μ_c the friction coefficient between adjacent staves. Equation 7 yields hoop tension requirements that are only about 10% of the hoop's yield strength at most.

A more common mode of wind failure is a local "snap-through" of the flat arch of the cylindrical wall (see Fig. 2). It is obvious that wall stiffness is again an important parameter in this type of failure because the failure mechanism is identical to that of wall buckling. There is little information available on the magnitude of hoop tension required to prevent this local type of failure.

Failures from high wind loadings have been reported only for empty silos. From this it may be concluded that the body of silage acting together with the silo provides enough strength and rigidity to resist wind loading. This supposition is reinforced by reports of partially filled silos that collapsed in severe wind storms only to the top of the silage.

A final failure mode that may occur when integrity of the wall is lacking is caused by asymmetric internal silage pressure from uneven filling. Again, little is known of the forces involved, but the underlying cause of difficulties is most likely insufficient tension in the hoops.

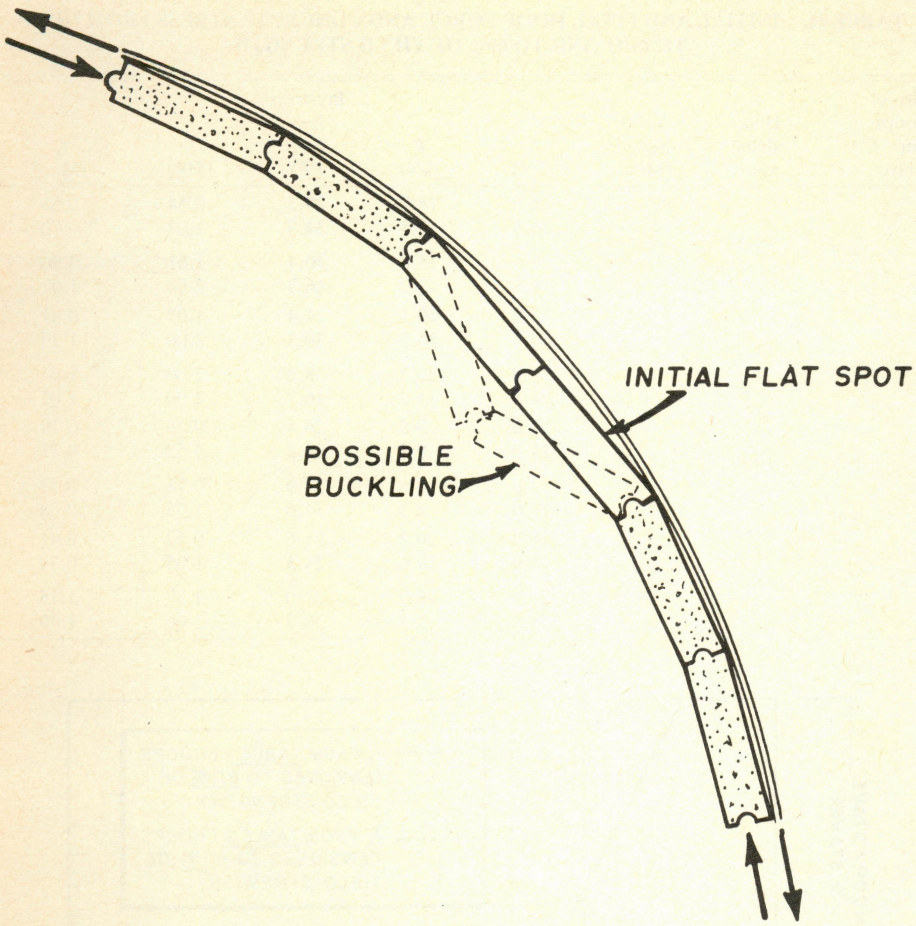

Figure 2. Local buckling failure of a stave tower silo wall due to wind loading.

TABLE I. INITIAL AND FINAL HOOP FORCE AND CONCRETE STRESS FROM HOOP TENSIONING TO 80% OF YIELD STRENGTH

No. of hoops per stave	Hoop diam (mm)	Yield strength (MPa)	T_i (kN)	T (kN)	Prestress loss T_i-T (%)	f_{c_i} (MPa)	f_c (MPa)
1	14.3	275	35.3	25.8	26.9	0.71	0.52
2			35.3	23.9	32.4	1.43	0.96
3			33.0	20.3	38.5	2.00	1.23
4			24.8	13.2	46.7	2.00	1.07
1	14.3	550	70.7	54.3	23.2	1.43	1.10
2			49.5	34.5	30.3	2.00	1.39
3			33.0	20.3	38.5	2.00	1.23
4			24.8	13.2	46.7	2.00	1.07
1	10.0	275	17.3	13.1	24.0	0.35	0.27
2			17.3	12.7	26.7	0.70	0.51
3			17.3	12.2	29.5	1.05	0.74
4			17.3	11.7	32.2	1.40	0.95
1	10.0	550	34.6	27.5	20.4	0.70	0.56
2			34.6	26.6	23.1	1.40	1.07
3			33.0	24.4	26.0	2.00	1.48
4			24.8	17.3	30.0	2.00	1.40

Based on the foregoing, the hoop tension criterion that provides some residual compression at full load (Eq. 3 or 4) might be relaxed somewhat for stave tower silos provided that even filling can be guaranteed. If this is done the vertical joints will open at some stage of internal loading and the silage body will have to be relied upon to provide some of structure's rigidity. It is, of course, essential that the wall return to a state of compression when the internal load is removed.

DESIGN EXAMPLE

Before discussing a tower silo design example it is informative to examine values of prestress losses based on the earlier work (Kleywegt and Jofriet 1979) and on the initial prestress value restrictions of the design criterion in the previous section. Four combinations of 10.0- and 14.3-mm diameter hoops of 275- and 550-MPa steel have been considered. Calculations were carried out for 1, 2, 3 and 4 hoops per 762-mm long stave. The results of the analyses are shown in Table I. Results for T_i, the initial prestress force in the hoop, T, the prestress force remaining after all losses, ΔT, the loss of prestress are shown. The associated initial and final concrete stresses in the wall, f_{c_i} and f_c are also provided.

The results in Table I are based on the assumption that all recommendations to reduce prestress losses made by Kleywegt and Jofriet (1979) have been followed. Accordingly, the sum of the friction and elastic shortening loss was assumed to be 14% of T_i. The creep strain loss was assumed to be $20A_s/A_c$ times the remainder of the prestress force. Finally a shrinkage loss of 16 MPa was subtracted.

The results in Table I indicate that the percent prestress loss can be reduced by reducing the size and by increasing the yield strength of the hoops. The "improved" 10-mm diameter, 550-MPa hoops have strength about equal to the "standard" 14.3-mm, 275-MPa hoops. The percent loss of the "standard" hoops is from 1.3 to 1.5 times that of the "improved"; more importantly, the concrete compressive stress after losses, f_{c_i} is considerably greater for the "improved" hoops.

The prestress force and resulting concrete stress have also been determined for a reduced initial tensioning of the hoop to 60% of the yield strength, as specified by the CFBC (1977). The lower initial tension results in greater prestress loss in the hoops and lower compressive stresses in the concrete wall of the silo for those cases in which T_i is governed by the hoop strength (see Table II).

The value of f_c in Tables I and II will be used to analyze a typical 19.8-m high tower stave silo of 4.88-m diameter and 65-mm wall thickness. Hoops are of 14.3-mm diameter and the hooping schedule is established on the basis of strength only using an allowable hoop stress of 60% of an assumed yield strength of 275 MPa (see Fig. 3). Assuming initial tensioning to 80% of 275 MPa and measures to minimize prestress losses, the compressive circumferential stress in the stave may be expected to vary as shown by the dashed line in Fig. 3. The internal silage pressure (Eq. 2) reduces the compression in the silo wall by an amount shown by the sloping line in Fig. 3. Where the precompression exceeds the stress change caused by the internal load, the silo wall will not remain in compression under full design load. Where this is not the case, the staves will lose contact in the vertical joints.

If, in the above example, maintaining a residual compression in the staves were adopted as a design criterion, the stave schedule would have to be revised to one hoop per stave in the top 8 staves, two hoops per stave in the next 12 staves; this constitutes a 6% increase over the original strength design.

Also shown in Fig. 3 are the values of f_c resulting from a reduced hoop prestress of 60% of the yield strength. It may be observed that the available precompression is insufficient over most of the height of the silo to provide any residual compression after application of the internal silage pressure.

The exact same design procedure was repeated for the "improved" 10.0-mm diameter 550 MPa yield strength hoops (Fig. 4). The area of a 10.0-mm bar is almost one half that of a 14.3-mm bar, and the total strength is about the same, providing a hooping schedule that is virtually the same as in Fig. 3. Again the available precompression, f_c, in the concrete from a hoop prestress of 80% of the yield strength is shown with a dashed line. This time f_c is adequate to provide a residual compression at full load. The concrete stress resulting from a 60% prestress is shown also. Again, this reduced prestress leads to separation in the vertical joints if the original hooping schedule is adhered to.

It must be remembered that the hooping schedule of the second example (Fig. 4) requires about 50% of the weight of steel

TABLE II. INITIAL AND FINAL HOOP FORCE AND CONCRETE STRESS FROM HOOP TENSIONING TO 60% OF YIELD STRENGTH

No. of hoops per Stave	Hoop diam (mm)	Yield strength (MPa)	T_i (kN)	T (kN)	Prestress loss $T_i - T$ (%)	f_{c_i} (MPa)	f_c (MPa)
1			26.5	18.7	29.3	0.54	0.38
2	14.3	275	26.5	17.3	34.9	1.07	0.70
3			26.5	15.8	40.4	1.61	0.96
4			24.8	13.2	46.7	2.00	1.07
1			53.0	40.1	24.4	1.07	0.81
2	14.3	550	49.5	34.5	30.3	2.00	1.39
3			33.0	20.3	38.5	2.00	1.23
4			24.8	13.2	46.7	2.00	1.07
1			13.0	9.5	26.4	0.26	0.19
2	10.0	275	13.0	9.2	29.2	0.52	0.37
3			13.0	8.8	31.9	0.78	0.53
4			13.0	8.5	34.6	1.05	0.68
1			25.9	20.3	21.6	0.52	0.41
2	10.0	550	25.9	19.6	24.3	1.05	0.79
3			25.9	18.9	27.0	1.57	1.15
4			24.8	17.3	30.2	2.00	1.40

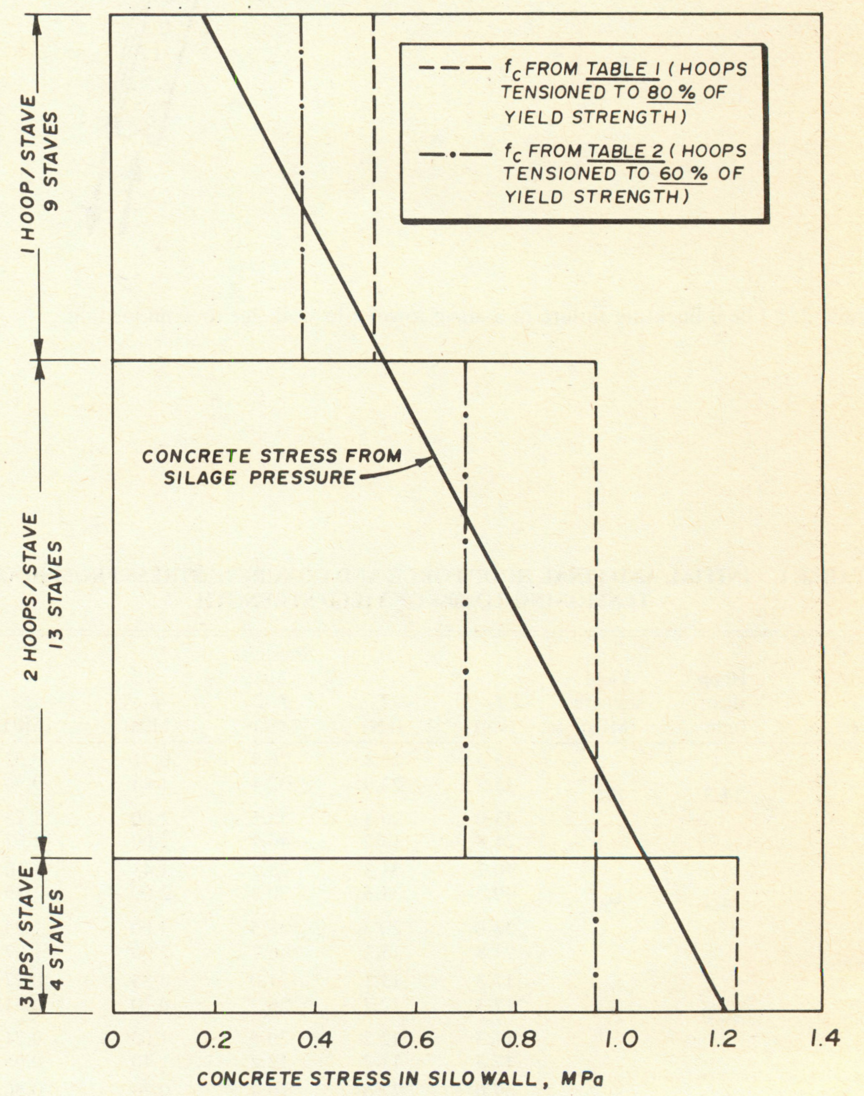

Figure 3. Circumferential stresses in silo wall from silage pressure and hoop tension for a 4.88-m diameter by 19.8-m high silo with 14.3-mm diameter, 275-MPa yield strength hoops.

used in the hooping schedule of example one (Fig. 3).

SUMMARY AND RECOMMENDATIONS

A number of design criteria have been put forth for the structural design of concrete stave structures. The design criteria are based on prestressed concrete design principles and recognize that prestress losses will reduce the amount of tension put in the hoops at the time of erection. The application of criteria to the design of a silage storage structure shows that with proper measures to minimize prestress losses, the desirable criterion of some residual compressive stress in the stave wall at full load can be achieved with little or no extra hooping.

The following are recommended alternatives to the present CFBC 1977 clauses on concrete stave silo design. They summarize the various recommendations in this paper:

1. The structural design of stave silo construction shall employ accepted engineering principles commonly used in the design of posttensioned segmental concrete structures.
2. The ultimate circumferential tensile strength of the hoops shall be equal to or greater than the tension in the hoops caused by the factored internal pressure; the ultimate tensile strength of the hoops shall be subject to a capacity reduction factor of 0.8 for steel without, and 0.9 for steel with a guaranteed yield strength; the load factor for liquid pressures shall be 1.4, for silage and like materials 1.7.
3. The hoop tension at time of erecting shall not exceed 80% of the yield strength of the hoop material.
4. The resulting compressive stress in the staves at time of erecting shall not exceed 2 MPa.
5. The structural design of the hoops and the hoop tension shall take account of all losses of prestress including elastic shortening, friction between hoops and staves, and creep and shrinkage of the staves; the determination of the loss of prestress shall take into account the construction methods used and the age of the staves.
6. The hoops shall be tensioned such as to provide, after all losses, a small residual compressive circumferential stress in the staves at full load.

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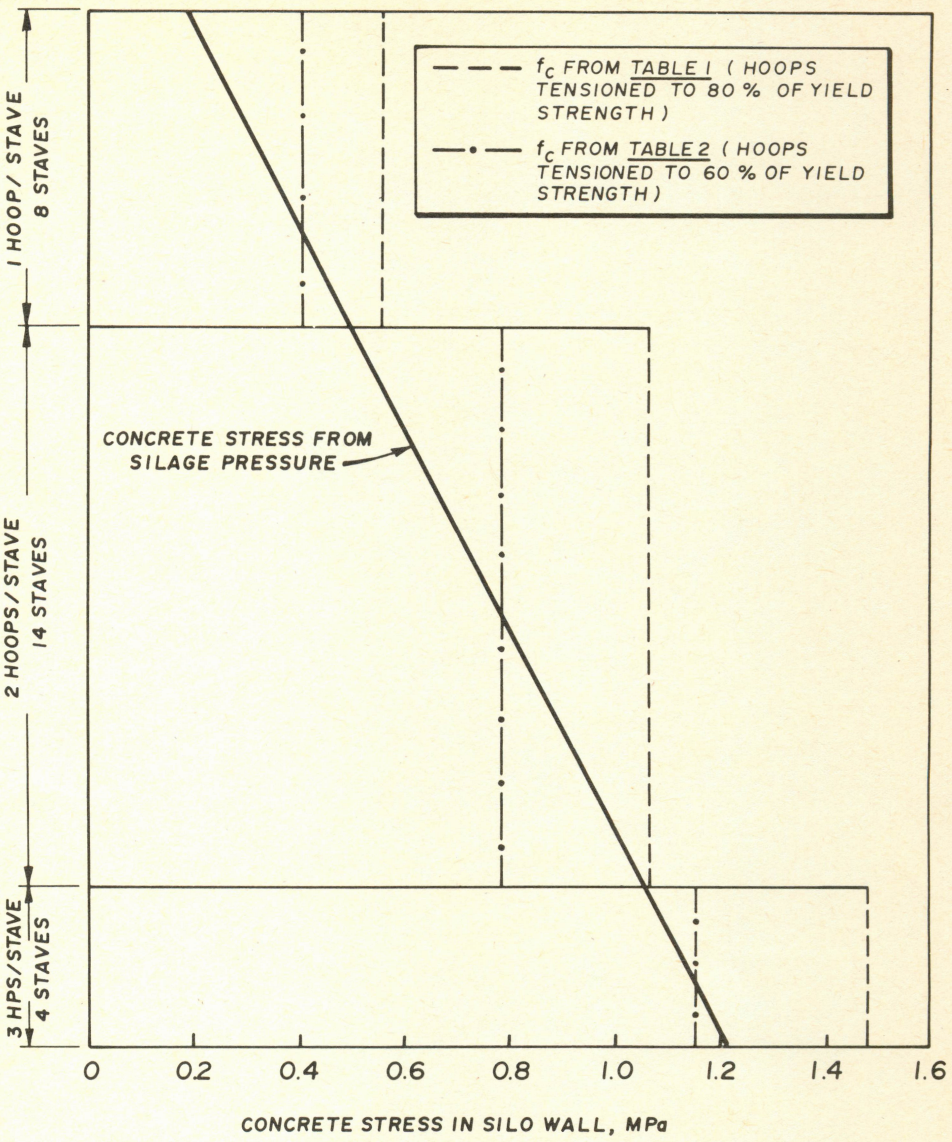

Figure 4. Circumferential stresses in silo wall from silage pressure and hoop tension for a 4.88-m diameter by 19.8-m high silo with 10.0-mm diameter, 550-MPa yield strength hoops.

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